The Quantitative Assessment of River Reach Morphology

By

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Abstract

Rivers are an integral part of the earth's ecological, hydrological and physical systems, and also provide an indispensible range of services to humans. However, despite our strong dependence on rivers, human activities, and particularly the increased pressure on water resources, have resulted in a general degradation of river health world-wide. The long-term sustainability of many river systems is dependent on their successful management, and a key component of river management is to simply and meaningfully order streams into natural or arbitrary groups based on common characteristics. Such classification can assist in the management of rivers by increasing understanding of river form and process amongst the general complexity found in rivers. River classification has been central to developing an understanding of the links between hydrology, geomorphology and ecology and also allows knowledge from a particular river type at one location to be extrapolated to other locations of the same type, thus reducing resourcing requirements.

Although possessing a relative abundance of water in comparison to many other regions, north-eastern Tasmanian faces pressures on water resources similar to those experienced elsewhere. In recent years, considerable effort has been directed towards achieving a balance between abstraction and environmental flows in north-eastern Tasmanian rivers, but this process has been complicated by the wide variety of riverine environments and channel and floodplain forms found in the region, and by the relatively few studies that have investigated the region's geomorphology, hydrology, and ecology.

Two approaches to classification have been adopted in the management of Tasmanian rivers. A nested hierarchical river classification system has been developed for Tasmania, and has formed the basis of a comprehensive river health assessment methodology. However this approach is relatively resource intensive, requiring data to be collected and expert analysis to be applied at different scales. In addition the large number of groups (river types) that this model produces means that developing relationships between flow alteration and physical and ecological response for each river type is impractical. A second approach has been the development of a broad two-classed model that classifies rivers on the basis of hydrological variability. Although this is an objective and quantitative model requiring few resources, the wide variety of river types included within each of the two classes mean that only the most generalised models linking hydrology, geomorphology and ecology can be developed. While each of these classification systems could be considered to fulfil the purpose for which they

were designed, the lack of a simple and objective method to classify rivers into a reasonable number of meaningful classes on the basis of channel morphology has limited the development of predictive ecosystem models to link the physical and ecological responses of north-eastern Tasmanian rivers to altered flows.

The aim of this study was to develop an objective and quantitative method to group north-eastern Tasmanian rivers and streams into hydromorphologically meaningful groups. This was achieved through several sub-studies; estimation of the magnitude and frequency of small floods, investigation of bankfull channel morphometry, analysis of the first order estimates of peak discharge of small floods, and assessment of the hydromorphological characteristics of different river basins.

The magnitude-frequency of small floods (average recurrence interval < 5 years) was estimated by analysis of data from 13 north-eastern Tasmanian stream-gauging stations. Empirical comparisons were made between flood frequency estimates based on the annual series data set, those based on the partial series, and the Langbein method of converting annual series average recurrence intervals to partial series intervals. Annual series estimates were found to be one third the magnitude of partial series estimates at low average recurrence intervals, but converged with partial series estimates at around 5 years. The methods developed in this chapter are used in a later sub-study to develop relationships between discharge and catchment area for north-eastern Tasmanian Rivers.

Two quantitative methods for determining bankfull stage from plotted channel cross-sections, the minimum width-to-depth ratio and the first maximum of the bench-index were evaluated against qualitative estimates of bankfull stage on 89 cross-sectional surveys undertaken at nine river reaches in north-eastern Tasmania. Results indicated that while neither method offered a suitable stand-alone means for estimating bankfull stage, they may in combination provide a means to approximate the range of bankfull stage and serve as a useful adjunct to other methods. The results also highlight the large variability in channel morphology along a reach. The results from this sub-study were used to assist in the identification of bankfull channel morphology parameters in a later assessment of hydromorphological characteristics of rivers and development of groupings.

First order estimates of the peak discharge of small floods at ungauged sites in north-eastern Tasmania were investigated through the development of power-law equations relating the peak discharge of floods with average recurrence intervals ranging from 1.1 to 10 years to catchment area (A_d). Using data from 13 stream gauging stations, the analysis suggested that the discharge associated with a flood with two year average recurrence interval was estimated by $A_d^{0.9}$. Intra-regional variation in the relationship was investigated and differences were found between those rivers which drain to the north coast and those which drain internally or to the east coast. The uncertainty and error associated with the study was also identified and discussed. Intra-regional variation in the relationship between discharge and catchment area identified a group of northward draining rivers in north-eastern Tasmania that plotted as negative residuals and a group of internally draining sites which plotted as positive residuals.

Three hydromorphological characteristics of north-eastern Tasmanian rivers, drainage density, bankfull frequency and stream-power, were investigated using the results from the first order estimates of peak discharge of small floods sub-study. The range and variation in drainage density values was examined and found to broadly reflect variations in precipitation, elevation and geology. Variation in drainage density was found to be correlated to changes in the density of higher order streams, with little variation occurring in the density of first and second order streams. The range and variation in drainage density values was examined and found to broadly reflect variation in precipitation, elevation and geology. The two groups of rivers identified previously were found to have different drainage density ranges. Catchments draining northwards or eastwards to the coast were found to have drainage densities > 2 km km^{-1}, while internally draining catchments were found to have drainage density < 2 km km^{-1}.

The estimation of bankfull discharge in north-eastern Tasmanian rivers was investigated, and peak discharge with an average recurrence interval of two years was proposed as a proxy for bankfull discharge. Attempts to accurately measure bankfull discharge at the study sites using field techniques were unsuccessful, as was the use of commonly used flow resistance equations. Large variances were found between estimates from different flow resistance equations, particularly at sites with deeper channels and high hydraulic radius.

Estimates of peak discharge of small floods developed previously were used to develop suitable methods to estimate stream-power values. Substantial variability in downstream trends in stream-power was found in the Pipers, Ringarooma and Scamander rivers. These rivers were found to have different longitudinal trends and to deviate from the general downstream stream power trends found elsewhere. There was some evidence of an association between channel morphology and stream power, with high *WD* values/ low *R* values occurring at locations with high stream power.

The river and catchment metrics developed in earlier chapters were then used in conjunction with univariate and multivariate statistical analysis in an attempt to develop meaningful hydromorphological groupings of north-eastern Tasmanian rivers. using objective and quantitative methods. A range of univariate and multivariate statistical techniques was applied to a dataset consisting of 164 channel cross-sections from thirteen sites, and the results were assessed against a separate dataset containing 58 cross-sections from 15 sites. A strong source of underlying variability in the channel morphdataset was found to occur along an orthogonal axis which had high values of width-to-depth ratio at one end and high hydraulic radius values at the other. The variability of bankfull channel morphology both along a reach and between sites was examined, and Principal Components Analysis and agglomerative clustering used to examine the underlying structure in the data and identify the best low-dimensional representation of the variability in channel morphology.

The river and catchment metrics developed in earlier chapters were then used in conjunction with multivariate statistical analysis of channel cross-sectional data from field surveys to investigate variability in channel morphology and develop a quantitative morphological typology. A strong source of underlying variability in the dataset was found to occur along an orthogonal axis which had high values of width-to-depth ratio at one end and high hydraulic radius values at the other. While analysis was able to identify two groupings with membership based on either high width-to-depth ratio or high hydraulic radius, methods to derive the groupings of sites based on channel parameters using remote parameters were generally unsuccessful; combinations of the remote parameter values were unable to reproduce natural grouping identified using channel parameters. However drainage density was identified as a strong remotely sensed predictor variable. The results suggest that localised and reach scale factors have more influence on channel morphology than catchment scale controls in north-eastern Tasmanian rivers.

The overall study results suggest that north-eastern Tasmanian rivers are highly variable and have characteristics different from those found elsewhere. This has implications for the use of remotely sensed data and GIS tools in the study of regional hydromorphological characteristics.

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List of Abbreviations

AEP	Annual Exceedance Probability
ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
ASL	Above Sea Level
BMCMC	Bayesian Markov Chain Monte Carlo
CFEV	Conservation of Freshwater Ecosystems Values
CI	Confidence Interval
COAG	Council of Australian Governments
CV	Coefficient of Variation
DEM	Digital Elevation Model
DPIPWE	Department of Primary Industries, Parks, Water and the Environment
EDA	Environmental Domain Analysis
ELOHA	Ecological Limits of Hydrological Alteration
GIS	Geographic Information Systems
GPD	Generalized Pareto Distribution
GPS	Global Positioning System
HV	High Variability
IEA	Institution of Engineers Australia
LV	Low Variability
LWD	Large Woody Debris
NSE	The Nash-Sutcliffe Efficiency statistic
NWC	National Water Commission
NWI	National Water Initiative
PBIAS	Percent Bias
PC	Principle Component
PCA	Principle Components Analysis
POT	Peaks Over Threshold
QQ	Quantile–Quantile
RMSE	The Root Mean Square Error
RRMSE	The Real space relative Root Mean Square Error in percentage
RSE	Standard error of the regression
RSR	The Root Mean Square error
SD	Standard Deviation
TEFF	Tasmanian Environmental Flows Framework
TRCI	Tasmanian River Condition Index
WFD	Water Framework and Habitats Directives
WLS	Weighted Least Squares Regression
WMP's	Water Management Plans

List of Symbols

A_d	Catchment Area (km^2)
T	Average recurrence interval (years)
T_P	Average recurrence interval determined using the partial series (years)
T_A	Average recurrence interval determined using the annual series (years)
n	The number of observations in a dataset
m	The rank of a flood event in a streamflow data set
α	Plotting position bias constant for flood frequency analysis
k	The number of flood events in a streamflow data set
PS	Partial Series flood events data set
AS	Annual Series flood events data set
LC	Langbein adjusted flood frequency estimates
W	Channel width (m)
D	Channel depth (m)
W_i	Channel width at stage ‘i’ (m)
D_i	Channel depth at stage ‘i’ (m)
RWD	Ratio of channel width to channel depth
BI	Bench Index
WD	Minimum width-to-depth ratio
D	Mean channel depth (m)
A	Channel cross-sectional area (m^2)
Y_i^{obs}	The ith observation for the constituent being evaluated
Y_i^{sim}	The ith simulated value for the constituent being evaluated
Y_i^{mean}	The mean of observed data for the constituent being evaluated
BF	Qualitative estimate of bankfull stage
Q_T	Flood discharge with an average recurrence interval equal to T years
a	The theoretical discharge per unit catchment area (m^3s^{-1})
b	Scaling factor in the relationship between catchment area and discharge
Q_{pred}	The predicted discharge (m^3s^{-1})
Q_{obs}	The observed discharge (m^3s^{-1})
D_d	Drainage density (km/km^2)
ΣL	The total length of streams within a catchment (km)
SO	Stream Order (Strahler)
Q_{bf}	Bankfull discharge (m^3s^{-1})
V	The average velocity of water in a channel (ms^{-1})
ε	Random error
df	Degrees of freedom
K	A coefficient in flow resistance equations for estimating discharge
R	The hydraulic radius (m)
S	The friction slope of a river channel (m/m)
n	Manning’s resistance coefficient
T_{bf}	The average recurrence interval of bankfull stage (years)

Ω	Stream power (Wm^{-1})
ρ	The density of water (1000 kgm^{-3})
g	The gravitational constant (9.8 ms^{-1})
TRAIN	Training group
TEST	Test group
P	Wetted perimeter (m)
E	Elevation (m)

Chapter 1 Introduction and Aims

1.1. Rivers and their study

Rivers are an integral part of the earth's ecological, hydrological and physical systems and also provide humans with water for domestic, agricultural and industrial use, as well as food, energy, minerals and fertile soils for agriculture. People use rivers for travel, transport, recreation, and as a means of disposing of wastes, and most of the world's major cities are located on a river. Despite our strong dependence on rivers, human activities have resulted in a general degradation of river health worldwide (Poff et al., 2010). Efforts to sustain biodiverse and functional river ecosystems now represent one of the greatest environmental challenges for the twenty-first century, with ultimate success in sustainable river management depending implicitly upon the ability to conceptualise river systems in a clear, systematic and organised manner (Brierley and Fryirs, 2008).

River systems have been conceptualised at least since Herodotus (c484-c426) contemplated the silting of the Nile River delta (Tinkler, 1985), but modern consideration of rivers may be said to have commenced with the series of works that culminated in the Geographic Cycle of Davis (1889). Building on concepts that had been around for millennia, Davis's scheme attempted to order rivers into stages of youth, maturity and old age, and was the first to provide a working terminology and place fluvial concepts within the general scientific framework of geology (Tinkler, 1985). Another noteworthy step in the comprehension of river systems, which accompanied the channel network studies of Horton (1945), was a general shift from description to quantification in fluvial geomorphology (Doyle and Julian, 2005). The move towards quantification was accompanied by the accumulation of quantitative data from varying regions of the world, and allowed geomorphologists to characterise broad forms, to speculate on the probable mechanistic drivers of these patterns and to synthesise landforms into classifications (Renschler et al., 2007).

1.2. River classification

1.2.1. Classification schemes

Classification is both the process of ordering objects into groups based on common characteristics, as well as the systems that result from that process (Kondolf et al., 2003). Similar to a taxonomy of organisms, classification attempts to distinguish and group distinct types or classes (Karr, 1999), with the specific approach varying according to the goals and purposes. The many reviews and summaries of river classification systems (Kellerhals et al., 1976, Tinkler, 1985, Naiman et al., 1992, Kondolf, 1995, Newson et al., 1998, Kondolf et al., 2003) generally highlight that the approach of each scheme is related to its objectives, which are often linked to specific management problems, various scales and different geographical settings (Kondolf et al., 2003).

Classification is used in geomorphology to identify common processes and morphologies, separate disparate ones, and to assist in understanding the causal relationships between form and process (Nanson and Knighton, 1996). The first published comprehensive study on river channel pattern (Leopold and Wolman, 1957) was a form based classification of meandering, braided and straight channels. The highly influential work of Schumm (1977), used river processes to classify alluvial channels based on sediment load. The form based methodology developed by Rosgen (1994), which is the best known and most widely used stream classification in the United States (Juracek and Fitzpatrick, 2003) has been criticised for ignoring process (e.g. Juracek and Fitzpatrick, 2003, Simon et al., 2007). Many other classification schemes exist (e.g. Montgomery and Buffington, 1997, Montgomery, 1999, Church, 2002, Schmitt et al., 2007) with an example widely used in Tasmania (Table 1.1) and other states of Australia being the River Styles methodology of Brierley and Fryirs (2000), which includes elements similar to the system of Rosgen (1994) but analyses river character and behaviour at a range of scales.

While the dynamics and morphology of a river is shaped by local features, its structure and dynamics are ultimately determined and controlled by the characteristics of the surrounding catchment. Recognition of the larger-scale controls on smaller-scale systems led to the development of the spatially nested river classification hierarchy of Frissell et al. (1986) (Figure 1.1) where geographically independent classes are delineated using morphological features that are assumed to control processes at a variety of nested spatial scales within the watershed (Snelder and Biggs, 2002). More recently, there has been a recognition of the importance of bottom-up, trans-scale processes in geomorphology (Heritage et al., 2000, Poole, 2002). In recognition that broad-scale parameters in the nested hierarchy generally determine the boundary conditions and range of behaviour of physical processes at smaller scale units, the river styles classification of Brierley and Fryirs (2000) analyses river character and behaviour at four interlinked scales: catchments, landscape units, river styles (reaches), and geomorphic units.

River styles is an open ended system where practitioners generate their own river types based on evidence and lines of reasoning that demonstrate how particular process-form relationships generate different types of rivers within any given catchment. However this makes methodological makes methodological 'quality control' of projects a major concern, and leaves the 'use' of the classification to be determined through local means (Tadaki et al., 2014).

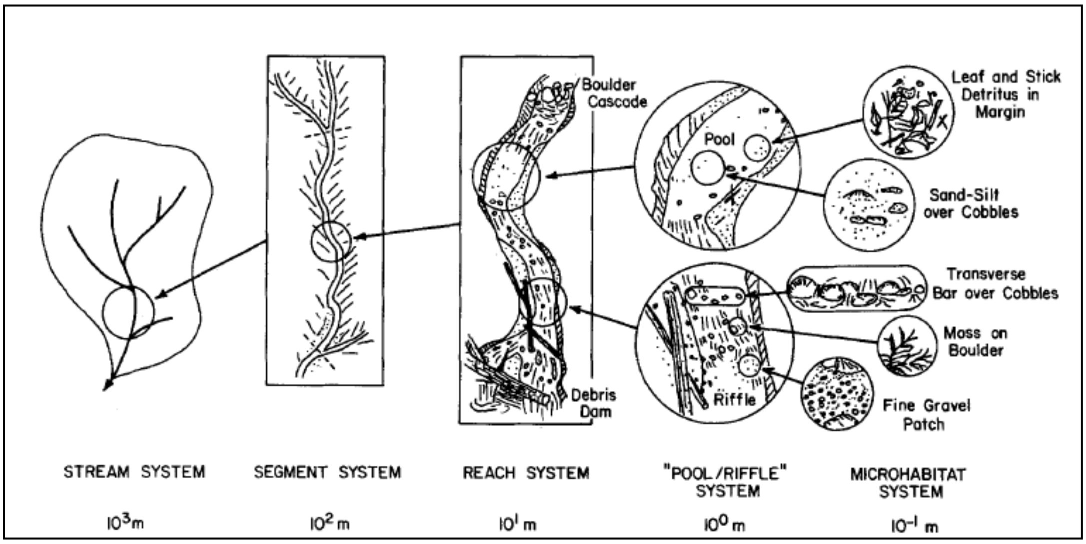


Figure 1.1. The hierarchical organisation of a stream system and its subsystems, with approximate linear spatial scale, appropriate to second or third order mountain streams (From Frissell et al., 1986)

Tadaki et al. (2014) point out that despite the veneer of objectivity granted by the use of various statistical procedures, approaches to river classification ultimately rely upon expert judgement and intuition to classify phenomena and consequently classification schemes are not objective or value-neutral, but instead are institutional projects that propose and embed particular priorities and nature–society relations.

1.2.2. The identification of homogeneity within the heterogeneity of river systems

The river reach is the most frequently used scale in river classification, and is also the most common unit of description and study among fluvial geomorphologists, aquatic biologists and ecologists. The wide and diverse use of the term has resulted in the reach being sometimes the least physically discrete unit in the river classification hierarchy (Frissell et al., 1986). In a generic sense a reach may be considered as any segment of river defined for any purpose, but many specific definitions for specific applications have been developed. The river reach has variously been defined as a section of river: between tributary junctions (DPIW, 2008a); between breaks in channel slope, local sideslopes, valley floor width, riparian vegetation, and bank material (Frissell et al., 1986); along which boundary conditions are sufficiently uniform (i.e., there is no change in the imposed flow or sediment load) such that the river maintains a near consistent structure (Kellerhals et al., 1976); of relatively homogenous associations of topographic features and channel geomorphic units, which distinguish them in certain aspects from adjoining reaches (Bisson and Montgomery, 1996); and with no significant change in discharge or sediment load (Thomson et al., 2004). Reaches have also been variously called macro-reaches, zones, functional process zones and hydro-geomorphic patches (Dollar et al., 2006) and descriptions of the length of reaches range from meters (Frissell et al., 1986) to kilometres (Ladson et al., 1999). In this study, a reach is defined as a relatively homogenous segment of river extending from one tributary junction to the next, that has a characteristic structure in terms of channel geometry (size and shape), channel planform, and the assemblage of geomorphic units throughout its length which distinguishes it from congruent reaches (cf., Brierley and Fryirs, 2000).

River reaches are central to river restoration and management efforts. Successful river management requires management actions to be considered in relation to the character and behaviour of any given reach (Brierley and Fryirs, 2009), and reaches are an integral part of the river classification and assessment schemes that are used to make decisions about management (Clark et al., 2008). Disturbance of the equilibrium of fluvial systems is also most easily observed at the reach scale (Bornette et al., 2008).

A common criterion in the many definitions of a river reach is the identification of areas of relative homogeneity in geomorphic form and/or function amongst the heterogeneity of river systems (Kellerhals et al., 1976, Church, 1992, Bisson and Montgomery, 1996). The assessment of 'homogenous' river character and behaviour in a reach will vary depending on the parameters investigated and the scale at which the assessment is applied. Several neighbouring landscape elements delineated at a given spatial scale amalgamate into a single encompassing element if observed at a sufficiently coarse spatial scale, and the original elements can be subdivided into several component elements if observed at a finer spatial scale (Poole, 2002). Downstream trends in most river geomorphic parameters at coarse scales are well recognised, with discharge, channel width, channel depth and channel cross-sectional area generally increasing in the downstream direction (Figure 1.2). However the changes occurring at the finer scales are less well understood.

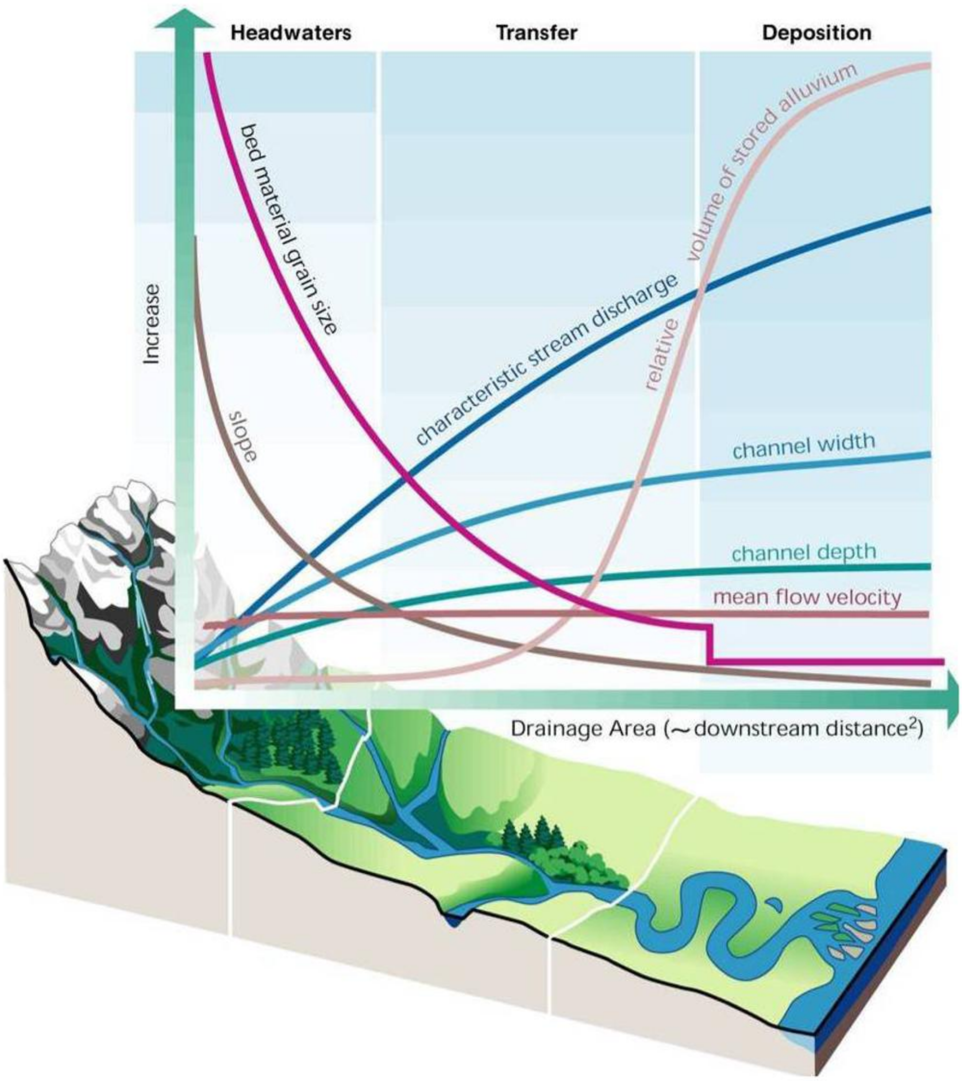


Figure 1.2. Broadscale downstream trends in river hydromorphological parameters (From FISRWG 1988 reproduced in Welsh (2011))

Similarly, while broad scale classifications such as the delineation of rivers into headwaters (erosion), transfer (transport), and deposition zones (Schumm, 1977) (Figure 1.2), are generally understood, at a finer scale, more complex relationships can be identified. The processes shaping rivers operate across different scales, creating various functional and physical boundaries that do not always coincide (Figure 1.3), and consequently the delineation of meaningful boundaries is one of the major challenges for fluvial geomorphological classification.

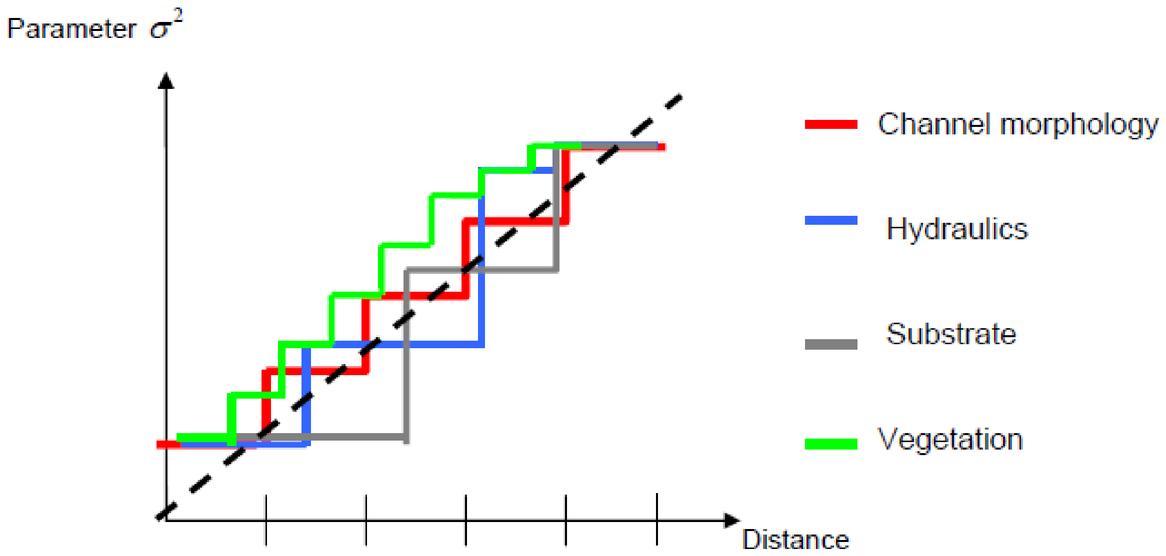


Figure 1.3. Cumulative variability of several different habitat parameters, each according to its own pattern and potentially independent of the discrete geomorphic hierarchical scales (From Zavadil, 2009).

1.2.3. River classification parameters

All classification schemes face the philosophical difference as to whether river systems are composed of a continuum of channel morphology, resulting in arbitrary groupings, or discrete types of channels bounded by geomorphic thresholds or controlled by local influences, allowing the development of a natural classification (Kondolf et al., 2003).

While reaches may be defined as homogenous sections of rivers, in reality it may be difficult to delineate a reach amongst the natural heterogeneity of form and process which occurs in rivers as a result of both downstream trends and local variation of both a random and systematic nature (Knighton, 1998). This may especially be the case in alluvial channels where patterns are generally believed to form a continuum rather than discrete types, and distinctions between morphologic forms are fuzzy and complex (Ferguson, 1987, Knighton and Nanson, 1993, Bledsoe and Watson, 2001). Consequently the identification, demarcation and justification of classes and boundaries is extremely problematic for geomorphology (Thorn, 1988), and has been much studied (Table 1.1).

Table 1.1. Examples of studies of transitions and boundaries applicable to river reach or river style delineation.

Type of boundary, transition or threshold	Parameters studied	Sources
Channel form and planform		
Channel form	Discharge, slope, sediment supply, bank stability, valley confinement	(Fotherby, 2009)
Channel form	Hydraulic data	(Bledsoe and Watson, 2001)
Channel form	Relief, lithology, runoff	(Brussock et al., 1985)
Channel form and function	Antecedent fluvial and alluvial topography	(Phillips and Slattery, 2008)
Channel form	Large infrequent disturbances	(Parsons et al., 2006)
Reach transition	Slope	(Dollar et al., 2006)
Channel planform	Stream power, slope, substrate	(Marren et al., 2006)
Single to multiple channels	Discharge, hydraulic geometry, sediment	(Burge, 2004)
Meandering to braided	Channel morphology	(Carson, 1984b)
Meandering to braided	Discharge, bedgrain size, slope	(Carson, 1984a)
Meandering to braided	In-channel bars	(Crosato and Mosselman, 2009)
Meandering to braided	Slope, discharge, channel bank strength	(Simpson and Smith, 2001)
Braided to meandering	Landuse, vegetation, slope, morphology	(Marston et al., 1995)
Braided, meandering, straight	Hydraulic data	(Ferguson, 1987)
Braided, meandering, straight	Hydraulic data	(Ferguson, 1987)
Straight, meandering and braided to anastamosing	flow strength, bank erodibility, sediment supply	(Knighton and Nanson, 1993)
Anabranching rivers	Slope, discharge, grain size	(Burge, 2006)
Anabranching rivers	Discharge, sediment size, morphology	(Nanson and Knighton, 1996)
Anabranching rivers	History, morphology, bed grain size, flow	(Burge, 2006)
Hydraulic geometry	Discharge	(De Rose et al., 2008)
River to floodplain	Discharge, slope, longitudinal profile	(Jain et al., 2008)
Substrate		
Gravel to sand	Discharge, slope, profile, grain size	(Knighton, 1991; Knighton, 1999)
Gravel to sand	Shear stress	
Gravel to sand	Slope, sediment supply	(Smith and Ferguson, 1995)
Gravel to sand	Chironomidae fauna	(Scholl and Haybach, 2004)
Rock, gravel and sand-bed channels	Morphology, planform, hydrology, grain size	(Howard, 1987)
Sand to mud	Stream power, slope, substrate	(Marren et al., 2006)
Substrate composition	Grain size, hydraulic data	(Thompson and Croke, 2008)
Other		
Tributary confluences	Basin size and shape, drainage density, network geometry	(Benda et al., 2004)
Tributary confluences	Morphology, velocity, particle size	(Wallis et al., 2008)
Tributary confluences	Discharge, bed load grain size	(Rice et al., 2006)

Geomorphological classification schemes have different approaches to the conflict between a continuum of channel features and discrete types. Rosgen (1994) recognised a continuum of river morphology within and between stream types in his classification scheme. Bisson and Montgomery (1996) suggested the determination of reach boundaries between the river types they identified was a matter of some judgement, and Brierley and Fryirs (2005) described the identification of boundaries between river styles as entailing a degree of subjectivity, with the criteria used in their differentiation usually forming part of a continuum along which breaks may be abrupt, gradual, diffuse or even alternating (Brierley and Fryirs, 2005). Consequently, the classification of rivers into different classes may entail a degree of subjectivity, as the criteria used in their ordering may be part of a continuum depending upon the scale at which it is considered (Table 1.2).

Table 1.2. Possible parameters to use in river classifications and the suggested scales over which each parameter operates.

Parameter	Approximate scale (m)
Valley setting	
Valley confinement	10^0 - 10^3
Geology	$10^0 – 10^2$
Antecedant morphology	$10^0 – 10^2$
Channel planform	
Channel pattern	$10^0 – 10^2$
Tributary junction	$10^0 – 10^2$
Sinuosity	$10^0 – 10^2$
Channel morphology	
Bankfull width	$10^{-2} – 10^0$
Depth	$10^{-2} – 10^0$
Surface flow type	$10^{-2} – 10^0$
Bank morphology	$10^{-2} – 10^0$
Bank composition	$10^{-2} – 10^0$
Substrate composition	$10^{-2} – 10^0$
Slope	$10^0 – 10^2$
Width/depth ratio	$10^{-2} – 10^0$
Cross sectional area	$10^{-2} – 10^0$
Wetted perimeter	$10^{-2} – 10^0$
Froude number (Fr)	$10^{-2} – 10^0$
Hydrology	
Discharge (various)	$10^{-1} – 10^0$
Stream velocity	$10^{-1} – 10^0$
Stream power	$10^{-1} – 10^0$
Other	
Aquatic vegetation	10^0 - 10^2
Riparian vegetation	10^0 - 10^2
Large woody debris	10^0 - 10^2
Anthropogenic	
Dams and weirs etc	10^0 - 10^3
Landuse change	10^0 - 10^3

A wide range of features and processes may be used to define discrete reaches, with the variables chosen dependant on the objectives of the study. However ultimately reach boundaries must reflect discernible changes to river character and behaviour (Brierley and Fryirs, 2005). Amongst the variety of river classifications, Schmitt et al. (2007) found common classification criteria included climate, geology, relief (at the basin scale), valley bottom and channel morphology, channel pattern, gradient, grain size, in-stream features, and particularly stream power.

1.2.3.1. Discharge

Discharge, the flow of water down a river, is the independent variable that largely determines the size of river channels and influences planform through the amplitude and wavelength of meanders (Schumm, 1977). Discharge and sediment is conveyed into the main river channel through tributaries. Natural divisions of river channels often occur at a tributary junction. Tributaries convey water and sediment into the main channel, and the morphological conditions near channel junctions may differ from those in reaches located upstream or downstream (Benda et al., 2004). Wallis et al. (2008) found a step-increase in channel width in post-confluence channels in studies of Australian rivers. In addition to the discrete or natural discontinuities in channel gradient and morphology, bed sediment size and flow properties that may occur at the tributary junctions, strong environmental gradients have also been found to occur up and downstream of confluences (Rice et al., 2006). Despite its influence on channel morphology, hydrology and ecology, discharge has not proved to be an effective criterion for classification, except where river size is a primary consideration (Knighton, 1998). More commonly discharge has been used to derive other classification parameters such as stream power, which has been widely used in the study of channel form, boundaries and thresholds (Chang, 1985, Nanson and Barbettitaylor, 1995, Simpson and Smith, 2001, Brierley and Fryirs, 2005, Marren et al., 2006, Harvey et al., 2008, Jain et al., 2008) and river classification schemes (e.g. Ferguson, 1987, Nanson and Knighton, 1996, Schmitt et al., 2007).

1.2.3.2. Valley setting

Although channel processes are driven by flow and sediment supply, the range of channel adjustments that are possible are often restricted by the valley setting (Charlton, 2008), which influences the valley confinement and slope, geology and geomorphology and channel network characteristics. Valley confinement refers to the extent to which lateral migration and channel change is inhibited by contact with the walls of the alluvial valley (Phillips, 2008). Valley confinement acts as a primary control on the differentiation of geomorphic process zones along rivers and has been used as a discriminating factor in a number of geomorphic classifications (e.g. Rosgen, 1994, Montgomery and Buffington, 1997, Brierley and Fryirs, 2000). Changes to valley width may result in significant transitions in in-stream river character and behaviour (Brierley and Fryirs, 2005), and have been demonstrated to be the dominant factor in determining channel pattern in some rivers (Fotherby, 2009). However determining valley confinement requires some degree of expertise in landscape interpretation. Valley slope affects the channel slope, which has been closely associated with changes in substrate (Knighton, 1991, Knighton, 1999). Channel slope, in conjunction with discharge, determines stream-power, which has been widely used to determine thresholds for channel planform (Marren et al., 2006).

Slope, in conjunction with discharge, has been studied to determine thresholds for change in channel planform and substrate (Table 1.1). If not influenced by uplift or variations in bedrock, the gradient of a stream will usually show a downstream decrease (Figure 1.2.) that is associated with an increase of discharge and a decrease in sediment size (Schumm, 1977).

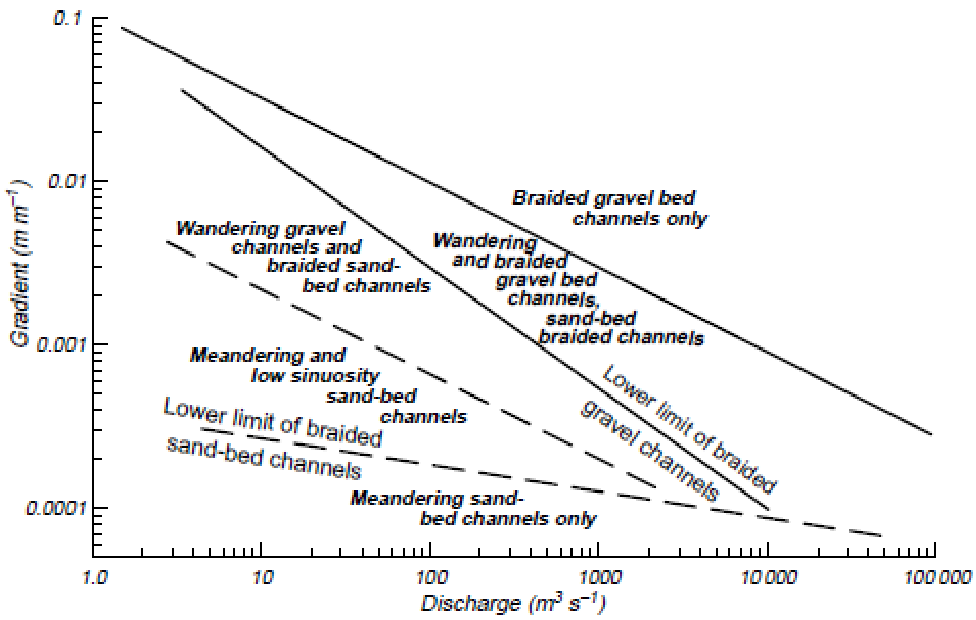


Figure 1.4. Fields of river channel morphological pattern within the domain of slope versus channel-forming discharge (From Church, 2002).

1.2.3.3. Litholology

Reach morphology may be associated with direct geological controls on channel processes. Geology affects the nature of sediment supply and acts as a constraint on channel adjustment through its influence on bed and bank material composition (Knighton, 1998). Lithology can also effect basin relief (Miller et al., 1990), and has been shown to play a significant role in influencing river structure and function at the reach scale (Harvey et al., 2008). Geological disturbance can disrupt channel networks and long profiles, with channel adjustments at the reach scale including changes in slope, lateral tilting and localised faulting (Charlton, 2008). Inherited geomorphic features such as antecedent fluvial and alluvial topography have also been shown to influence channel form (Phillips and Slattery, 2008, Phillips, 2008).

1.2.3.4. Channel planform

Channel planform has been used in the classification of rivers at least since Leopold and Wolman (1957) attempted to determine discharge and slope thresholds for straight, meandering and braided channels. While it has been suggested that channel planform may be stage dependant (Kellerhals et al., 1976), many other studies have investigated the variation in form and process between straight, meandering and braided channels (Carson, 1984a, Carson, 1984b, Ferguson, 1987, Bledsoe and Watson, 2001, Burge, 2004, Crosato and Mosselman, 2009), and the types of channels studied has broadened to include anastamosing (Knighton and Nanson, 1993), anabranching (Nanson and Knighton, 1996, Burge, 2006), and multiple channel river patterns (Burge, 2004). Anthropogenic influences on channel planform have also been considered (Marston et al., 1995).

1.2.3.5. Substrate composition

The composition of the substrate is a common parameter in stream classification. The size of material on the bed of a river has a significant influence on sediment transport characteristics, resistance properties and channel form adjustment, with an overall tendency for bed material to decrease downstream (Knighton, 1999). The reach typically possesses a characteristic range of channel bed materials (Frissell et al., 1986) and a large number of studies have compared substrate composition between different types of rivers (Howard, 1987, Smith and Ferguson, 1995, Marren et al., 2006). A number of studies have considered the downstream variation in substrate composition in the disturbed Ringarooma Catchments in north-eastern Tasmania (Knighton, 1991, Knighton, 1999).

1.2.3.6. Anthropogenic effects

Over human history rivers and river catchments have become increasingly modified by landuse change within catchments, as well as by direct disturbance to river courses and channels (Brierley and Fryirs, 2005). Most rivers throughout the world have been subjected to some form of human disturbance, and in south-eastern Australian rivers many rivers have become deeper, wider, straighter and more homogenous in the period since European settlement (Brierley et al., 2005). Dams reduce or modify the discharge of rivers, with downstream geomorphic consequences to channel shape and gradient (Knighton, 1998), and water extraction for irrigation reduces summer discharges with potential consequences for aquatic biodiversity (Arthington et al., 2006). Altered floodplain drainage, changed river flow regimes and catchment landuse change combines with riparian vegetation removal to cause bank erosion and increase channel capacity (Brierley and Fryirs, 2005). River channels can also be modified by the addition of sediments by mining waste disposal, such as in the Ringarooma River in north-eastern Tasmania where both direct and indirect changes to the morphology of reaches has occurred as a result of mine tailings (Knighton, 1998).

1.2.3.7. Ecological effects

Geomorphology provides the physical habitat for ecological systems, but ecological systems also influence the hydro-geomorphology of rivers and streams. Stream bank vegetation has been shown to influence channel width and form (e.g. Brown, 1997, Brooks et al., 2003, Anderson et al., 2004, Gurnell et al., 2009), at the point where it occurs or downstream (Wipfli et al., 2007), while in-stream vegetation has been shown to influence channel form, point bar formation, and meander migration (Blanka and Kiss, 2006). Recent studies have emphasised the interdependence between biological and physical forms and processes (Corenblit et al., 2007, Fisher et al., 2007, Viles et al., 2008). Coarse or large woody debris (LWD) has also been shown to influence channel and floodplain morphology in rivers around the world (Gurnell and Petts, 2002, Gurnell et al., 2009), as well as in Australia (Nanson and Barbettitaylor, 1995, Brooks et al., 2003). Interactions between LWD and the stream channel stimulate structural heterogeneity (Naiman et al., 2005) and may initiate processes such as channel anabranching (Nanson and Knighton, 1996).

1.3. Form and process in rivers

A fundamental control on the form of a river is the composition of the surface material it passes through. Rivers that are surrounded by a floodplain formed of material transported and deposited by river are able to make large scale changes in channel dimensions and planform, while rivers that are controlled by bedrock are not (Jerie, 2003). Alluvial rivers are rivers in which the channel bed and banks are composed of mobile sediment and soil and in which discharge is the independent variable that largely determines the size and shape of river channels and influences planform through the amplitude and wavelength of meanders (Schumm, 1977). Because human settlement has often occurred on the floodplains of alluvial rivers, they have long been a subject for human contemplation. Alluvial rivers are shaped by the magnitude and frequency of the floods that they experience (Knighton, 1998), and in recent time they have been a focus for studies attempting to develop an understanding between the form of rivers and the processes operating upon them.

Central to these studies have been the concepts of a channel-forming or dominant discharge, the discharge at which most sediment is transported over a long period of time (Benson, 1966), and bankfull stage, the stage at which the river channel is full and above which flow would exceed the active channel banks (Riley, 1972). In a highly influential work, Wolman and Miller (1960) suggested that while discharge events of varying magnitude, frequency and temporal structure influence channel form, the channel morphology of alluvial rivers appears to be associated with flows at or near the bankfull stage. This correlation between channel shape and bankfull discharge has since been widely debated in Australia (e.g. Pickup and Warner, 1976) as well as elsewhere.

In reality it is a vast simplification to say that only one flood size is responsible for maintaining channel dimensions and in reality a range of flood sizes contribute (Jerie et al., 2003). Extreme flood events may substantially modify the river channel but occur rarely, in contrast to smaller discharges which, while individually may have little ability to modify the river channel, have a magnified contribution due to their high frequency. The frequency and variability of flows and the flood history also play an important role in alluvial river bank morphology. However ideas of a channel forming discharge to which the channel geometry becomes adjusted continue to be central to fluvial geomorphology studies (Doyle et al., 2007), with various models and generalisations realted to variability in channel and form process based on this concept. The magnitude and frequency of the most geomorphically effective flow has also been the subject of considerable debate (Leopold et al., 1964, Armstrong et al., 2012).

A strong theme in the study of alluvial channel form, and of fluvial geomorphology more generally, has been the dichotomy between broad generalisations and narrow specifics when trying to classify rivers. Rivers channels are often highly heterogeneous, with morphology seldom constant and often changing dramatically along a single reach. Standardized approaches to landscape classification sacrifice heterogeneity in order to generalize, treating landscape units as homogenous entities wherein all members of the same class are considered to be equivalent and interchangeable (Church, 2011). Brierley et al.(2013) suggest new approaches must be developed that move beyond the reductionist approaches to landscape analysis, realistically framing and interpreting specific (local) instances in relation to generalizable understandings of trends and patterns. More recently, large remotely sensed data sets and new GIS techniques are providing some of these new approaches. The 'riverscape' framework (Carbonneau et al., 2012) for example, offer new tools which promise to preserve variability and spatial relationships while considering entire river systems.

Brierley et al. (2013) argue that this requires 'reading the landscape', where a bottom-up, constructivist approach is applied to identify landforms, assess their morphodynamics, and interpret the interaction and evolution of these features at reach and catchment scales. In this approach contextualized, place-based understandings can be used to detect where local differences matter, thereby addressing concerns for the transferability of insights between locations and the representativeness of sample or reference sites.

Variability also exists in rivers at much large scales. Australian rivers have important differences from those in most other parts of the world, with lower discharge and more variable flow regimes (Finlayson and McMahon, 1988) and a sediment load dominated by fine suspended particles and a reduced coarse sediment load because of the stability of the continent and the almost complete absence of Quaternary glaciations (Tooth and Nanson, 1995). European settlement has resulted in substantial changes to Australian rivers and riparian areas, especially in the south-east. Typically, rivers lined by stands of forest, and with channels containing extensive volumes of woody debris before European settlement are today characterized by floodplains that have been cleared for agriculture and channels that have been desnagged for navigation or flood conveyance (Brooks and Brierley, 2002).

There have also been major changes to channel morphology in many south-eastern Australian rivers since European settlement, with many rivers becoming deeper, wider and straighter. Brooks and Brierley, (2002) suggest explanations for this change have focused on the nature of the Australian flood regime, and more specifically the extreme flood variability of Australian rivers (Finlayson and McMahon, 1988). These views suggest that the changes that have occurred fall within the natural range of variability of river behaviour, and that European clearance and riparian land use were contributing factors superimposed on this natural instability (Erskine and Warner, 1988). As a result of these differences, Australian rivers have been shown to have relationships between form and process that are different to those in most other parts of the world (Brierley and Fryirs, 2005). Many of the generalisations that were developed for rivers in other parts of the world are not relevant to Australian conditions.

Tasmanian rivers have significant differences to those in mainland Australia. Tasmanian hydrology is spatially highly variable, and although some rivers have a hydrology similar to mainland Australia, some Tasmanian rivers have been found to have low hydrological variability and relatively predictable flow regimes (DPIPWE, 2010). The highly variable Tasmanian landscape includes areas which have experienced relatively recent tectonic activity and glaciation (Sharples, 1996) and more extensive and intense periglacial processes than found elsewhere in Australia (Jerie et al., 2003). In addition, the large variations in hydrology and lithology have resulted in a wide variety of channel and floodplain forms across Tasmanian catchments (Cohen and Houshold, 2005). Also, the majority of Tasmanian rivers are unregulated, and many have large sections of forested floodplain, intact riparian vegetation and the presence of large woody debris (LWD). The material liberated by glacial and periglacial geomorphic processes in Tasmania has resulted in an increased coarse sediment load.

Rivers also change over time in response to floods or other natural or human induced disturbance. Some changes, such as the downstream movement of in-channel sand bars have little effect on channel morphology, while other events, such as a river avulsion, may have dramatic impacts on channel morphology. Increasingly in fluvial geomorphology, there has been an emphasis on the 'range of variability' of a river, in geomorphic, hydrologic and ecologic terms (Brierley and Fryirs, 2005). This has particular implications for river management where a 'stable' river has generally been the goal.

1.4. River management

1.4.1. The role of river management

Despite water being widely regarded as the most essential of natural resources, freshwater systems are directly threatened by human activities- globally 65% of river discharge, and the aquatic habitat supported by this water, is under moderate to high threat (Vörösmarty et al., 2010). While the alteration of flow, sediment, organic matter and thermal regimes has reduced the biological diversity and ecological integrity of freshwater ecosystems, the establishment of 'environmental flows' offers hope that many ecological and societal values of rivers can be maintained (Arthington et al., 2010). The need to retain 'environmental flows' , components of the natural flow regime in rivers retained for environmental purposes, is widely recognized as being essential for maintaining freshwater biodiversity and ecosystem processes, and achieving environmentally sustainable water resource management (Poff et al., 1997, Bunn and Arthington, 2002, Bobbi et al., 2013, Brisbane Declaration, 2007).

Developing a suitable methodology to determine appropriate levels of environmental flow has been the focus of a great deal of research (Gippel and Stewardson, 1998, Maddock, 1999, Reinfelds et al., 2004, DPIPWE, 2010). Recognition of the critical role of geomorphic properties in all aspects of river systems (Phillips, 2008) has seen many of these methodologies adopt a geomorphological template to model ecological systems. The ecological limits of hydrologic alteration (ELOHA) (Poff et al., 2010) is a synthesis of a number of existing hydrologic techniques and environmental flow methods to create a defensible and empirically testable relationships between flow alteration and ecological responses. ELOHA uses hydrological and geomorphological parameters to create a hydromorphological classification, and develops flow alteration–ecological response relationships for each of the hydromorphological types developed through a combination of existing hydroecological literature, expert knowledge and field studies across gradients of hydrologic alteration (Poff et al., 2010).

Australia is the driest inhabited continent (Post et al., 2012), possessing a very changeable climate (Garnaut, 2008) and highly variable streamflows (McMahon et al., 2007a). Although native species and systems have evolved to cope with the inherent shortage and variability of water in Australia (Lough and Hobday, 2011), increasing pressure on water resources and the modification of the landscape since European arrival has resulted in many rivers in South-eastern Australia experiencing a decline in ecosystem health (Balcombe et al., 2011). The predicted increased dryness and greater variability in weather in Southern Australia as a result of climate change (Urban and Daniels, 2006, Garnaut, 2008) is likely to exacerbate this decline. In Australia and elsewhere, increasing pressure on water resources combined with a decline in the health of aquatic systems has brought about a recognition that the aquatic environment is not a user of water in competition with other users, but is the base of the resource itself, which needs to be actively cared for if development is to be sustainable (Smakhtin, 2001). Federal and State Governments in Australia have acted jointly to reform and improve the management of water resources. These reforms included the establishment of the National Water Initiative (NWI), which sets out the basis on which freshwater resources are to be shared to support resilient and viable communities, healthy freshwater ecosystems and economic development, especially in the irrigated agriculture sector (NWC, 2011). To promote the objectives and outcomes of the NWI and to provide advice to the Council of Australian Governments (COAG) and the Australian Government on national water issues, the Federal Government has also established the National Water Commission (NWC) (NWC, 2013). Through these and other reforms substantial progress in the management of Australia's water resources has been made.

However, despite the effort devoted to establishing and implementing environmental flow regimes across Australia (including Tasmania), many of the approaches for determining environmental flow allocations lack data, transparency, and knowledge about important aspects of the aquatic ecosystem (Hart and Pollino, 2009). The absence of predictive ecosystem models, based on a scientific understanding of flow–ecosystem response relationships, remains a weakness in Australia's toolkit of water management models (NWC, 2011).

1.4.2. The management of Tasmanian rivers and streams

Tasmania has inherent differences to many regions of temperate mainland Australia in areas including riverine hydrology, water use and water management (Hardie et al., 2012). There is a relative abundance of water resources in Tasmania in comparison to many parts of Australia, and unlike much of mainland Australia, many rivers in rural areas of Tasmania are unregulated, with water allocations generally abstracted directly from river channels (Hardie et al., 2012). Despite these advantages and differences, water resources in Tasmania face similar pressures to those experienced nationally. Agricultural production, which is an important part of Tasmania's economy, relies heavily on the State's water resources. Over 50% of the 2,185 agriculture businesses in Tasmania use irrigation, compared with an average usage of 28% for Australia and 30% for Victoria (Chapman and Chapman, 2010). There are also plans by the State Government, supported by the Commonwealth Government, to increase the area of land under irrigated agriculture in Tasmania (Post et al., 2012). At the same time as the future demand on water resources increases, there is likely to be an accompanying decrease in rainfall and concurrent increase in potential evaporation as a result of climate change. While modelled estimates vary, it has been suggested that there may be an average decrease in surface water availability in Tasmania of 5% (Post et al., 2012), and up to a 14% reduction in total available yield in some north-eastern Tasmanian catchments by 2030 (DPIPWE, 2011). Across northern and eastern Tasmania, where agricultural production is most developed, water use is spatially localised and seasonally concentrated, and water use and environmental values across catchments are consequently highly variable (Bobbi et al., 2013).

Important steps have been taken by the Tasmanian Government to help address issues relating to pressure on Tasmania's water resources and to assist in their management. At the core of these improvements is the development of Water Management Plans (WMPs), which present a statement of the community's environmental, social and economic objectives for the relevant water resources and describe the water management regime that best gives effect to these objectives (DPIW, 2006b). To assist with this process, the Tasmanian Government developed the Tasmanian Environmental Flows Framework (TEFF). TEFF was developed to gather information about the links between characteristics of the flow regime, the physical form and spatial patterns of habitat within the channel, and the various processes that are driven by flow that impact on the character and function of freshwater and estuarine ecosystems (DPIPWE, 2010). The background to river classification is reviewed in detail in relation to north-eastern Tasmania in section 1.6, and the north-eastern region is first introduced in section 1.5.

1.5. North-eastern Tasmania

1.5.1. Setting

Tasmania is the southernmost state of Australia, with the main island extending across a latitudinal range of 39° 40′ to 43° 20′ S. The north-eastern region of Tasmania covers more than 6,500 km^2, almost one-third of the State's landmass (Figure 1.5), and is roughly delineated by the Tamar Estuary to the west and the South Esk River to the south. The region is divided into eight municipal areas, and the major industries are agriculture and forestry.

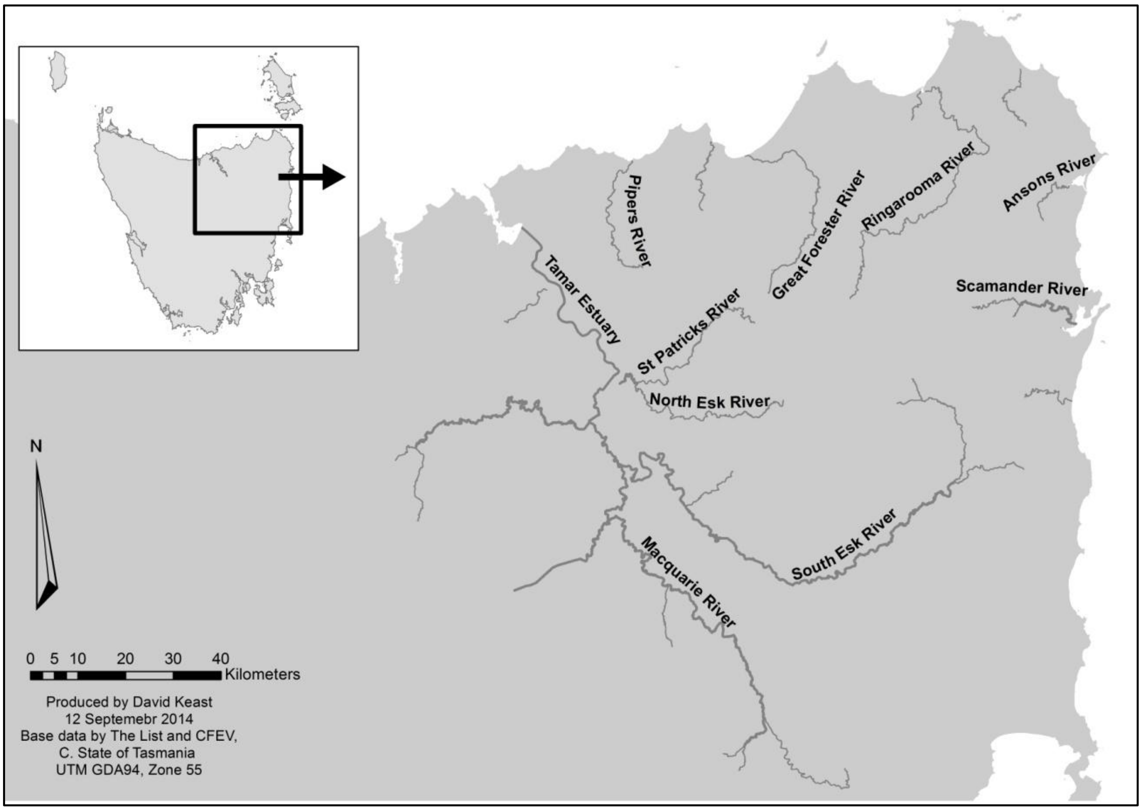


Figure 1.5. Major rivers in north-eastern Tasmania.

North-eastern Tasmania possesses surface geology and geomorphology distinct from the rest of Tasmania (Sharples, 1996). Formed on marine turbidite rocks (the Mathinna Group) intruded by granitic rocks and then tectonically transported to its present position, much of the region was subsequently uplifted over a long period. Thin sequences of Permian sedimentary rocks were laid down in some areas and later intruded by extensive sheets of dolerite magma during the Jurassic period. Block faulting caused increased landscape relief during the Cretaceous, and fluvial processes have been the major forces active in the region since the early Tertiary Period (Sharples, 1996). The present landscape includes mountain ranges underlain in their higher parts by Jurassic dolerite and Tertiary basalts and sediments on the valley floors that have frequently led to modifications of the drainage system (Spry and Banks, 1962, quoted in Caine, 1983).

The northeast region experiences a temperate marine climate, with temperatures generally influenced by distance from the coast. Rainfall is largely controlled by topographic change, and ranges from around 1200 mm on higher peaks to around 750 mm nearer the coast (Bureau of Meteorology, 1993). The region experiences high hydrological variability, as illustrated by the large difference in mean annual rainfall between the townships of Ross (as low as 510 mm) and Gray (over 1200 mm) (Bobbi et al., 1996), although the two locations are less than 75 km apart. Occasional very heavy rainfall events associated with high latitude ridging and the passage of intense low pressure systems occur about north-eastern Tasmania. These conditions can produce intense and sustained rainfall over periods up to 72 hours and have triggered major flooding events (McConachy et al., 2003, Fox-Hughes, 2009). Notable north-eastern Tasmanian rainfall events include the Pyengana storm of 9 December 1985, when rainfall rates in excess of 120 mm/h caused flash flooding and the 352 mm which fell at Cullenswood on 22 March 1974, the highest recorded rainfall in 24 hours in Tasmania (ABS, 2004).

1.5.2. The rivers and streams of north-eastern Tasmania

Tasmania has a wide variety of channel and floodplain forms over a small area as a result of high hydrological variability in combination with large variations in lithology and glacial history (Cohen and Houshold, 2005). Tasmanian rivers also possess significant differences to rivers of mainland Australia (See Section 1.3). North-eastern Tasmania reflects the differences and variability of wider Tasmania, with diverse riverine environments ranging from small headwater streams in uplifted erosional surfaces to broadwater features interrupting meandering alluvial rivers in unconfined settings and broad coastal sand bed rivers depositing and reworking large amounts of granitoid sediments transported from disturbed upper reaches.

Fluvial processes have been the major forces acting on the landscape in north-eastern Tasmania since the early Tertiary, and it has been suggested that many watercourses in the region possess underfit streams (Sharples, 1996). The major rivers in the region may be broadly divided into two groups. The first group, which includes the Brid, Great Forester and Ringarooma Rivers, contains rivers that arise in hills and mountain ranges not far from the coast and travel a short distance north or east before discharging into Bass Strait or to the east coast. The second group, which includes the North and South Esk, Macquarie, Isis, Lake, and Nile Rivers, contains rivers which drain internally and reach the ocean via the Tamar Estuary (Figure 1.5). The controls on river diversity in north-eastern Tasmania can be illustrated through examples.

Geology and geological processes play an important role in shaping the morphology of north-eastern Tasmanian rivers. The two rock types dominating surface geology, granite and dolerite, are believed to play an important role in determining both the morphology and hydrology of rivers in the region (DPIPWE, 2010).

Another example of the control surface geology exerts on Tasmania rivers is the lower South Esk River, which was diverted from its previous course to its present more westerly course by a basalt flow. The Tasmanian landscape includes areas which have experienced relatively recent tectonic activity and glaciation (Sharples, 1996). Where north-eastern Tasmanian rivers encounter Tertiary and Quaternary sediments river morphology can change in a range of ways. North-eastern rivers, including the South Esk and Macquarie Rivers, have developed sections of oversize channel; large broadwater pools, where highly erodible sediments have been exposed by the river. Conversely, the lower Lake River in north-eastern Tasmania has developed on a hardpan of tightly consolidated sediments and displays some of the characteristics of a bedrock controlled river (Jerie et al., 2003).

Australian rivers have been found to have important differences from those in most other parts of the world, with more variable flow regimes (Finlayson and McMahon, 1988), and a sediment load dominated by fine suspended particles with a reduced coarse sediment load because of the stability of the continent and the almost complete absence of Quaternary glaciations (Tooth and Nanson, 1995). The fluvial geomorphology of the rivers of Tasmania, a continental island located from around 41 to 43 degrees latitude also has significant differences from those of mainland Australia to the north.

Geological processes also play an important role on river channel morphology. The group of north-eastern streams which flow north to Bass Strait have had their course lengthened when land was uplifted out of Bass Strait, and as a consequence they have eroded a valley through the old coastal plain and created terraces on the lower reaches of these rivers (Jerie et al., 2003). Also in the north-eastern region, the area of the upper South Esk River catchment known as the Mathinna plains are the result of an uplifted erosional surface (Jerie, 2003).

Sharples (1996) considered much of the present landscape of north-eastern Tasmania to be a ‘fossil’ one, produced by past processes. He suggested that many of watercourses in north-eastern Tasmania are under-fit streams, occupying valleys too large for the present streams to have formed and containing coarse cobbles and boulders of a calibre beyond the capacity of the present stream to transport, except under exceptional flood conditions (Sharples, 1996). The conclusions of Sharples are supported by other studies which have found evidence of historical periods of greatly increased discharge in eastern Australian rivers (Nanson et al., 1992, Nanson et al., 2008).

Riparian vegetation and catchment land-use can often influence channel form. Riparian vegetation can influence the strength of channel banks, in-stream vegetation can slow water velocity and riparian vegetation can contribute LWD which has been shown to influence channel form. Upper reaches from two sites in north eastern Tasmania with similar surface geology and elevation illustrate this (Figure 1.6). This reach of the Great Forester River maintains riparian vegetation (although with introduced species), providing in stream structure and LWD while the nearby Brid River, has largely been cleared for agriculture, with the reach shown in Figure 1.6 showing bank slumping due to stock access to river banks.

Figure 1.6. Upper catchment streams with similar geology, catchment areas and elevations but very different riparian zones. Left, Brid River at Upper Brid Road (left) and Great Forester River at East Diddleum Road (right).

The geomorphic condition of rivers and streams in north-eastern Tasmania ranges from moderately to severely altered (DPIW, 2008b). Anthropogenic impacts on the geomorphology of Tasmania extend as far back as 35 and 30 ka, with evidence of increased erosion attributed to the significant ecological change brought about by aboriginal use of fire (McIntosh et al., 2009). European settlement greatly increased anthropogenic impacts. The Tertiary sediments on valley floors in the north-east have been a focus for mining activity (Jerie et al., 2003) since tin was first found on the Boobyalla River in the 1870's. Hundreds of widely distributed mining sites have been identified across north-eastern Tasmania, including many alluvial tin mining sites which have caused a disturbed landscape over the lower slopes of river and creek valleys (Gaughwin, 1992). As a result of this mining activity, the Ringarooma River in the north-east region (Figure 1.5) received large inputs of sediment which has caused substantial adjustments to its channel (Knighton, 1989). Other anthropogenic impacts occur to differing degrees at various locations in the region. These include the draining of wetlands, channel straightening, removal of riparian vegetation, and stock access to riparian zones (Figure 1.7), which can all influence channel morphology either directly or indirectly.

Figure 1.7. Bank slumping along the outside meander bend of an alluvial river at the Great Forester River at Ten Mile Track, exacerbated by the lack of riparian vegetation and unrestricted stock access.

1.5.3. The channel form and processes of north-eastern Tasmanian alluvial rivers

The use of two common channel morphometry parameters, hydraulic radius and the width to depth ratio, can help to illustrate the diversity of channel forms found in north-eastern Tasmanian alluvial rivers and the processes by considering their values in relation to the different channel forms of three unconfined alluvial rivers. A number of parameters are commonly used to measure channel morphometry, and more particularly bankfull channel geometry. The hydraulic radius (R) is a measure of the wetted perimeter in comparison to the cross-sectional area determined by the equation:

$$R = \frac{A}{P} \tag{6.1}$$

High values of *R* indicate a small wetted perimeter in comparison to the cross-sectional area. More complex channels will have lower *R* values than simple channels due to a larger wetted perimeter. The hydraulic radius is a measure of the flow efficiency of a channel that has been used in the Manning Equation and other discharge estimation equations (Dingman and Sharma, 1997). The hydraulic radius of the bankfull channel (*R*) at each cross-section was defined using equation 6.1 and the bankfull channel parameters *A* and *P* derived from the plotted cross-sections.

The width-to-depth ratio (*WD*) has been extensively used as a measure of channel shape and has also been found to be a determinant of channel planform (Li et al., 2013). High *WD* values suggest wide shallow channels, while low *WD* values indicate deeper narrower river channels. In this study, *WD* refers to the width-to-depth ratio of the bankfull channel at each cross-section as determined by dividing the bankfull channel width (*W*) by the mean bankfull channel depth (where the mean depth = *A* / *W*)) to arrive at the equation:

$$WD = \frac{W^2}{A} \tag{6.2}$$

The Third River at Paling Track (Figure 1.8.a) is a middle catchment third order stream at an elevation of 187 m ASL and with a catchment area of 4.4 km*2*. It has a relatively high *R* value and a low *WD* value, indicating a simple and efficient channel which is quite narrow in comparison to its depth. There is an indication of a small terrace on one bank. While this channel shape may arise for a number of reasons, the setting of this site suggests that the removal of vegetation since European settlement has increased surface runoff which has incised the previously smaller and shallower channel.

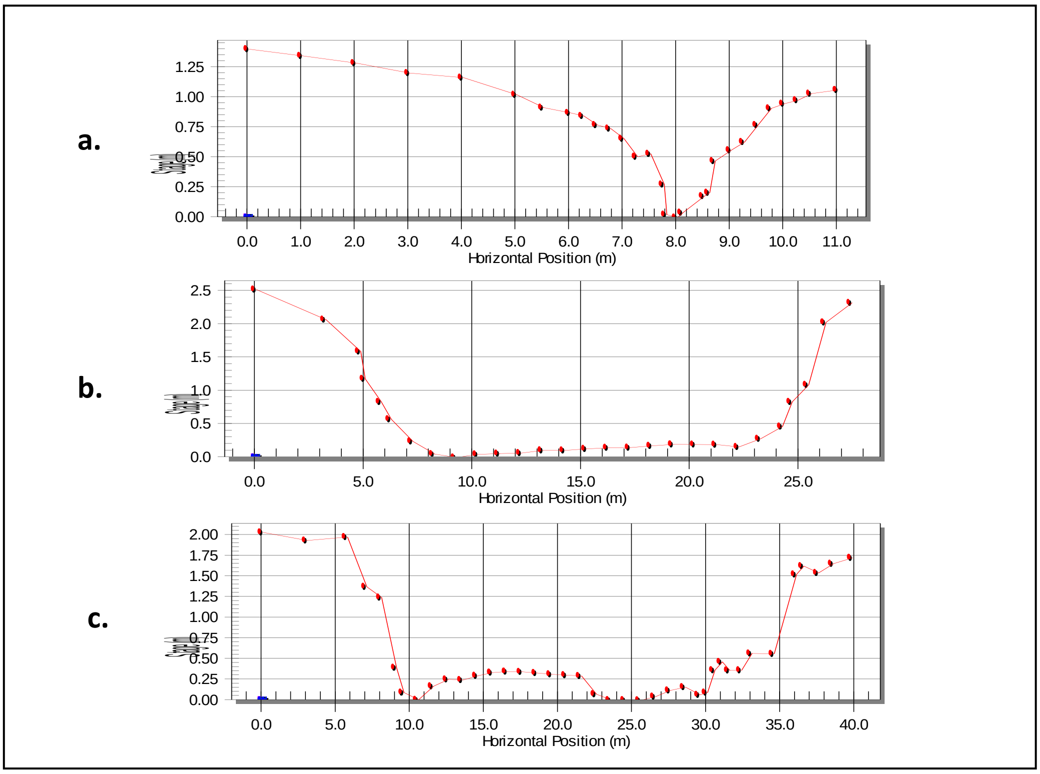


Figure 1.8. Channel cross sectional profiles for a) Third River at Paling Track; b) The South Esk River at Ormley; and c) The Ringarooma River at Wetlands.

The South Esk River at Ormley (Figure 1.9) is a middle catchment site (202 m ASL) located in the Fingal Valley, with a relatively large catchment area of 1360.5 km^2. The river at the study reach is composed almost entirely of dolerite rock of pebble and gravel size categories, with some boulder and bedrock present in sections where there is a change in gradient (DPIW, 2007). The river channel here is quite broad and deep (Figure 1.8.b), and consequently has medium *WD* values and high *R* values as it has a small wetted perimeter in relation to its cross sectional area. The river channel morphology here has become adjusted so it is very efficient at conveying discharge with minimum drag against the channel sides.

Figure 1.9. The South Esk River at Ormley (Source: DPIW, 2007).

The Ringarooma River at Wetlands (Figure 1.10) is a site at the bottom of its catchment (6 m ASL) which is composed largely of granitic sand carried down the river. Large amounts of material has been mobilised higher in the catchment as the result of historical mining activity. The baseflow channel is a shallow braided stream in a sand bed. Despite its catchment area being much smaller than that of the South Esk River at Ormley 878.1 km^2, its bankfull channel is much wider (Figure 1.8.c). It has a very high *WD* value, as the width of the channel is high in comparison to its depth. It has low *R* values as the large width of the channel results in a large wetted perimeter, creating a large frictional surface for water flow.

Figure 1.10. The Ringarooma River at Wetlands (Source: DPIW, 2007).

1.6. The classification of north-eastern Tasmanian rivers

The wide range of objectives of the various classifications, assessments and management plans that relate to north-eastern Tasmanian rivers and streams (Table 1.3) has resulted in many different methods being employed. Different spatial extents and scales also exist. While many of the documents use qualitative expert opinion to produce broad management strategies, others provide detailed reach-based actions, with a number of these documents using an interpretation of the River Styles framework (Brierley and Fryirs, 2000). Note that Department of Primary Industries, Parks, Water and the Environment (DPIPWE) documents, reports and plans relating to the development of WMP's for those north-eastern catchments that have them are not included in Table 1.3.

There have also been a number of studies of the fluvial geomorphology of north-eastern Tasmanian rivers and streams. Knighton (1987) carried out a regional analysis of streamflow characteristics for rivers in north-eastern Tasmania using streamflow records from thirteen gauging stations. Studies of the fluvial geomorphology of individual rivers in the region include the Lake River (Houshold, 1999) and the Pipers River (Locatelli, 2001, Ellison et al., 2002). Other studies have considered the impact of mining sediments on fluvial geomorphology of the Ringarooma River (Knighton, 1991, Knighton, 1999), suspended sediment transport in the North Esk River (Skirving, 1989) and the effect of logging on the geomorphology of small streams in the upper South Esk Catchment (Bunce, 2000, Bunce et al., 2001, Davies et al., 2005b). Studies have also been undertaken in relation to the impact of dams on the fluvial geomorphology of Brumby's Creek and the Macquarie River (Clerk, 1994).

A number of river classifications have also been developed for Tasmania. A geomorphic classification of Tasmania rivers was conducted by Jerie et al. (2003) who, using Environmental Domain Analysis (EDA), defined 90 geomorphic river regions or 'fluvial mosaics' in Tasmania based on lithology, climate, geomorphic process history, topography, vegetation and geological processes. Their work included a Tasmanian adaptation of River Styles known as Taswide styles, and data from their study contributed to the Conservation of Freshwater Ecosystems Values (CFEV) (DPIPWE, 2005) project and the Tasmanian River Condition Index (TRCI) (NRM South, 2009). CFEV is a Geographic Information Systems (GIS) database containing data sets based upon a combination of empirically modelled and other derived data. Rivers and streams are derived from a 1:25000 drainage layer, hydrological variables are based on the hydrological regionalisation of Hughes (1987), and the geomorphic component of the database is derived from 'fluvial mosaics' (Jerie et al., 2003) and from unpublished work by Koehnken (Davies et al., 2005a). TRCI is a comprehensive river health assessment methodology developed using the five components of aquatic life, hydrology, water quality, physical form (geomorphology), and the streamside (riparian) zone (South, 2009). The different components of TRCI are also based upon a geomorphic framework derived from the River Styles framework of Brierley and Fryirs (2000).

Table 1.3. Selected summary of river classifications, river care plans and management plans for north-eastern Tasmanian rivers and streams (Note: these documents are not listed in the reference list).

Document and author	River
Sprod, D., 2000. Break O'Day Rivercare Plan	Break O'Day
Cronin, S. J., 2001. Natural Resource Management Strategy - Upper Brumbys Catchment	Brumbys
Sprod, D., 2002. Elizabeth Catchment Rivercare Plan	Elizabeth
Sprod, D., 2003. Lower George Rivercare Plan	George
ID&A, 2000, Review of Stream Processes and Strategy Options for Three NHT Funded Work Sites	Ringarooma
Armstrong Agricultural Services, 2001. The Ringarooma Catchment	Ringarooma
Ketelaar, A., 2002.Rivercare Plan and Stage 1 Workplan for Lower Macquarie and South Esk Rivers	Macquarie
Hamlet, A., Askey-Doran, M., Jerie, K. and Cunial, S., 2003. Rivercare Plan for the Upper Macquarie Catchment	Macquarie
Sprod, D., Ketelaar, A., and Armstrong, D., 2002. River Management Plan-Pipers River	Pipers
Sprod, D., Ketelaar, A. and Armstrong, D., 2003. Rivercare Plan – Henrietta Plains	South Esk
Sprod, D. 2003. Upper South Esk River - Rivercare Plan	South Esk
St Patricks River Planning Kit	St Patricks

In general, two main approaches to river classification can be identified in the management of Tasmanian rivers and streams. The first approach is based around the nested hierarchical River Styles classification system (Brierley and Fryirs, 2000) and includes Tas Wide Styles, CFEV and TRCI. However this detailed reach based model is relatively resource intensive, requiring data to be collected and expert analysis to be applied at a number of different scales. In addition the large number of classes (river types) that have been produced for Tasmania using this model means that developing flow alteration – ecological response models for each river type is impractical.

The second approach to classification of Tasmanian rivers and streams has been developed by the Tasmanian Government with the objective of assisting in the development of relationships between flow alteration and physical and ecological response. This model uses a very broad two-classed model that classifies rivers on the basis on hydrological variability. Although this is an objective and quantitative model requiring few resources, the wide variety of different river types included within each of the two classes mean that only the most generalised models linking hydrology, geomorphology and ecology can be developed. While each of these classification systems could be considered to fulfil the purposes for which they were designed, the lack of a simple and objective quantitative method to classify rivers into a small number of meaningful classes on the basis of channel morphology has limited the development of predictive ecosystem models to link the physical and ecological responses of north-eastern Tasmanian rivers to altered flows.

1.7. Conclusion

Rivers are classified out of a basic desire for description and organisation of the world around us, to improve our understanding of fluvial form and processes, and to make better management decisions (Juracek and Fitzpatrick, 2003). This study assists in the management of rivers by investigating the development of an objective and quantitative morphological typology. The purpose of this study is to increase understanding of the hydromorphology of north-eastern Tasmanian rivers to assist in their management. The aim of the study is to develop an objective and quantitative broad morphological typology of Tasmanian rivers that can in the future be combined with existing hydrological typologies to develop a hydromorphological classification of Tasmanian rivers and streams.

1.8. Thesis overview

This thesis consists of a combination of chapters and stand-alone research papers. One paper (Chapter 2) has previously been published and is presented here unchanged except for formatting which has been standardised for ease of reading. Relevant acknowledgements, references, and appendices are included at the end of each chapter. In combination the different approaches of each chapter address the thesis aim by investigating aspects of geomorphology and hydrology that are relevant to the development of a hydromorphological typology of north-eastern Tasmanian rivers and streams. The chapter approaches are outlined below, and the findings of each are combined in the thesis conclusion to address the overall thesis objective.

Chapter 2: Flood frequency analysis using the partial and annual series

This study estimated the magnitude frequency of small floods ($T \leq 10$ years) for north-eastern Tasmanian streamflow stations using both partial and annual series data. These two methods were compared and assessed, along with the Langbein method of converting annual series average recurrence intervals to partial series values. This paper has been published in the journal *Water*: "Flood Estimation and Analysis in a Variable and Changing Environment" (2013), 5(4), 1816-1829; doi:10.3390/w5041816

Chapter 3: Comparison of quantitative techniques to determine bankfull stage.

This study evaluated two quantitative methods for determining bankfull stage from plotted cross-sections: the minimum width-to-depth ratio and the first maximum of the bench index. Each method was examined and compared to qualitative estimates of bankfull stage on 89 cross-sectional channel surveys of north-eastern Tasmanian Rivers.

Chapter 4: The relationship between discharge and catchment area for north-eastern Tasmanian Rivers.

This chapter developed power-law relationships between discharge and catchment area for north-eastern Tasmanian rivers and provided a method of estimating discharge at ungauged locations. It also examined the impact of the choice of annual or partial series flood frequency estimates on the scaling of the power-law relationship between discharge and catchment area.

Chapter 5: Three hydromorphological characteristics of north-eastern Tasmania.

This chapter investigated a number of river and catchment metrics from north-eastern Tasmania. Building on the results from Chapters 2, 3 and 4, this chapter evaluated drainage density, bankfull discharge recurrence frequency, and stream-power distribution in north-eastern Tasmania. The results from this chapter were used in the analyses conducted in Chapter 6.

Chapter 6: A morphological typology of north-eastern Tasmanian rivers.

This chapter used the river and catchment metrics developed in earlier chapters in conjunction with multivariate statistical analysis of channel cross-sectional data from field surveys to investigate variability in channel morphology and develop a quantitative morphological typology. The development of predictive equations to group sites into the developed typology based on stream-power and other remotely sensed parameters was then investigated.

Chapter 7: Conclusion.

This final chapter summarises the results from previous chapters, combining the different findings and considering the results as a whole. The overall results are placed within the context of the Tasmanian landscape and their transferability is considered. Finally, this chapter looks at emerging technologies, limitations of the study are discussed and directions for future study identified.

References

ANDERSON, R. J., BLEDSOE, B. P. & HESSION, W. C. 2004. Width of streams and rivers in response to vegetation, bank material, and other factors. *Journal of the American Water Resources Association,* 40**,** 1159-1172.

ARTHINGTON, A. H., BUNN, S. E., POFF, N. L. & NAIMAN, R. J. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications,* 16**,** 1311-1318.

ARTHINGTON, A. H., NAIMAN, R. J., MCCLAIN, M. E. & NILSSON, C. 2010. Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. *Freshwater Biology,* 55**,** 1-16.

AUSTRALIAN BUREAU OF STATISTICS (ABS), 2004, *Statistics – Tasmania*, viewed 10 September 2015, http://www.abs.gov.au/ausstats/.

BALCOMBE, S. R., SHELDON, F., CAPON, S. J., BOND, N. R., HADWEN, W. L., MARSH, N. & BERNAYS, S. J. 2011. Climate-change threats to native fish in degraded rivers and floodplains of the Murray–Darling Basin, Australia. *Marine and Freshwater Research,* 62**,** 1099-1114.

BENDA, L., POFF, N. L., MILLER, D., DUNNE, T., REEVES, G., PESS, G. & POLLOCK, M. 2004. The network dynamics hypothesis: How channel networks structure riverine habitats. *BioScience,* 54**,** 413-427.

BISSON, P. A. & MONTGOMERY, D. R. 1996. Valley segments, stream reaches and channel units. *In:* HAUER, F. R. & LAMBERTI, G. A. (eds.) *Methods in stream ecology.* San Diego: Academic press.

BLANKA, V. & KISS, T. 2006. Effect of riparian vegetation on Floodplain development: case study on River Maros (biogeomorphology). *Tajokologiai Lapok,* 4**,** 301-308.

BLEDSOE, B. P. & WATSON, C. C. 2001. Logistic analysis of channel pattern thresholds: Meandering, braiding, and incising. *Geomorphology,* 38**,** 281-300.

BOBBI, C. , FULLER, D. & OLDMEADOW, D. 1996. *South Esk Basin State of Rivers Report - a technical document presenting data collected during a study of rivers of the South Esk, Meander and Macquarie catchments during the period 1992–1995,* Resource Assessment Branch, Department of Primary Industry and Fisheries, Hobart.

BOBBI, C. J., WARFE, D. M. & HARDIE, S. A. 2014. Implementing environmental flows in semi-regulated and unregulated rivers using a flexible framework: case studies from Tasmania, Australia. *River Research and Applications***,** 30, 5, 578-592.

BORNETTE, G., TABACCHI, E., HUPP, C., PUIJALON, S. & ROSTAN, J. C. 2008. A model of plant strategies in fluvial hydrosystems. *Freshwater Biology,* 53**,** 1692-1705.

BRIERLEY, G. & FRYIRS, K. 2009. Don't fight the site: three geomorphic considerations in catchment-scale river rehabilitation planning. *Environ Manage,* 43**,** 1201-18.

BRIERLEY, G. J., BROOKS, A. P., FRYIRS, K. & TAYLOR, M. P. 2005. Did humid-temperate rivers in the Old and New Worlds respond differently to clearance of riparian vegetation and removal of woody debris? *Progress in Physical Geography,* 29**,** 27-49.

BRIERLEY, G. J. & FRYIRS, K. 2000. River styles, a geomorphic approach to catchment characterization: Implications for river rehabilitation in Bega catchment, New South Wales, Australia. *Environmental Management,* 25**,** 661-679.

BRIERLEY, G. J. & FRYIRS, K. 2008. Moves toward an end of river repair. *In:* BRIERLEY, G. & FRYIRS, K. (eds.) *River Futures:An Integrative Scientific Approach to River Repair.* Washington: Island Press.

BRIERLEY, G. J. & FRYIRS, K. A. 2005. *Geomorphology and River Mangement: applications of the river styles framework,* Malden MA, Blackwell Publishing.

BROOKS, A. P., BRIERLEY, G. J. & MILLAR, R. G. 2003. The long-term control of vegetation and woody debris on channel and flood-plain evolution: insights from a paired catchment study in southeastern Australia. *Geomorphology,* 51**,** 7-29.

BROWN, A. G. Biogeomorphology and diversity in multiple-channel river systems. 1997. Blackwell Science Ltd, 179-185.

BRUSSOCK, P. P., BROWN, A. V. & DIXON, J. C. 1985. Channel Form and Stream Ecosytem Models. *Journal of the American Water Resources Association,* 21**,** 859-866.
BUNCE, S., MCINTOSH, P., DAVIES, P. E. & COOK, L. S. J. 2001. Effects of pre-Code forest clearfelling on the geomorphology and sedimentology of headwater streams in upland granite terrain, Tasmania. *Third Australian Stream Management Conference:, 27 - 29 August 2001.* Brisbane.
BUNCE, S. E. 2000. *The fluvial geomorphology and sedimentology of class 4 streams affected by clearfell logging in northeast Tasmania : choosing impact indicators* B.Sc. (Hons.), University of Tasmania.
BUNN, S. E. & ARTHINGTON, A. H. 2002. Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. *Environmental Management,* 30**,** 492-507.
BUREAU OF METEOROLOGY 1993. *Climate of Tasmania,* Canberra, ACT, Australian Government Pub. Service.
BURGE, L. M. 2004. Testing links between river patterns and in-channel characteristics using MRPP and ANOVA. *Geomorphology,* 63**,** 115-130.
BURGE, L. M. 2006. Stability, morphology and surface grain size patterns of channel bifurcation in gravel-cobble bedded anabranching rivers. *Earth Surface Processes and Landforms,* 31**,** 1211-1226.
CAINE, N. 1983. *The mountains of northeastern Tasmania: a study of alpine geomorphology*.
CAPART, H., BELLAL, M. & YOUNG, D. L. 2007. Self-similar evolution of semi-infinite alluvial channels with moving boundaries. *Journal of Sedimentary Research,* 77**,** 13-22.
CARBONNEAU, P., FONSTAD, M., Markus, W. & Dugdale, S. 2012. Making riverscapes real. *Geomorphology*, 137(1), 74–86.
CARBONNEAU, P & PIEGAY, H. 2012. Introduction: The growing use of imagery in fundamental and applied river sciences. *In* CARBONNEAU, P & PIEGAY, H. (eds) *Fluvial Remote Sensing for Science and Management*, Wiley-Blackwell, Chitchester.
CARSON, M. A. 1984a. The meandering-braided river threshold-a reappraisal. *Journal of Hydrology,* 73**,** 315-334.
CARSON, M. A. 1984b. Observations on the Meandering-Braided River Transition, The Canterbury Plains, New Zealand: Part Two. *New Zealand Geographer,* 40**,** 89-99.
CHANG, H. H. 1985. River Morphology and Thresholds. *Journal of Hydraulic Engineering,* 111**,** 503-519.
CHAPMAN, M. & CHAPMAN, L. 2010. Water Security Outlook for Tasmanian irrigated dairy farms.
CHARLTON, R. 2008. *Fundamentals of Fluvial Geomorphology,* New York, Routledge.
CHURCH, M. 1992. Channel morphology and typology. *In:* CALOW, P. & PETTS, G. E. (eds.) *The rivers handbook: hydrological and ecological principles.* Malden, Massatuches: Blackwell Scientific Publications.
CHURCH, M. 2002. Geomorphic thresholds in riverine landscapes. *Freshwater Biology,* 47**,** 541-557.
CLARK, J. S., RIZZO, D. M., WATZIN, M. C. & HESSION, W. C. 2008. Spatial distribution and geomorphic condition of fish habitat in streams: An analysis using hydraulic modelling and geostatistics. *River Research and Applications,* 24**,** 885-899.
CLERK, E. W. 1994. *Hydrological changes and geomorphological adjustments in Brumbys Creek and the Macquarie River since 1964 : effects of the Poatina Power Station* B.Sc. (Hons.), University of Tasmania.
COHEN, T. & HOUSHOLD, I. 2005. An introduction to river processes and river rehabilitation in Tasmania. DPIW.
CORENBLIT, D., TABACCHI, E., STEIGER, J. & GURNELL, A. M. 2007. Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: A review of complementary approaches. *Earth-Science Reviews,* 84**,** 56-86.
CROSATO, A. & MOSSELMAN, E. 2009. Simple physics-based predictor for the number of river bars and the transition between meandering and braiding. *Water Resour. Res.,* 45.
DAVIES, P. E., LONG, J., BROWN, M., DUNN, H., HEFFER, D. & KNIGHT, R. 2005a. The Tasmanian Conservation of Freshwater Ecosystem Values (CFEV) framework: developing a

conservation and management system for rivers. *In:* WWF-AUSTRALIA, I. A. (ed.) *The freshwater protected areas conference 2004.* Sydney.

DAVIES, P. E., MCINTOSH, P. D., WAPSTRA, M., BUNCE, S. E. H., COOK, L. S. J., FRENCH, B. & MUNKS, S. A. 2005b. Changes to headwater stream morphology, habitats and riparian vegetation recorded 15 years after pre-Forest Practices Code forest clearfelling in upland granite terrain, Tasmania, Australia. *Forest Ecology and Management,* 217**,** 331-350.

DAVIS, W. M. 1889. The rivers and valleys of Pennsylvania. *National Geographic***,** 182-253

DE ROSE, R. C., STEWARDSON, M. J. & HARMAN, C. 2008. Downstream hydraulic geometry of rivers in Victoria, Australia. *Geomorphology,* 99**,** 302-316.

DOLLAR, L. H., DOLLAR, E. S. J. & MOOLMAN, J. 2006. Development of an automated desktop procedure for defining macro-reaches for river longitudinal profiles. *Water SA,* 32**,** 395-402.

DOYLE, M. W. & JULIAN, J. P. 2005. The most-cited works in Geomorphology. *Geomorphology,* 72**,** 238-249.

DPIPWE 2005. *Conservation of Freshwater Ecosystem Values Project (CFEV) database*. Tasmania: Water and Marine Resources Division, Department of Primary Industries, Parks, Water and Environment.

DPIPWE 2010. Tasmanian Environmental Flows (TEFlows) Project Technical Report. *Water Assessment Aquatic Ecology Report Series.* Hobart, Tasmania: Water and Marine Resources Division, Department of Primary Industries, Parks, Water and Environment,.

DPIPWE 2011. Ringarooma River Catchment Stage II Hydrology Report. *Water Assessment Hydrology Report Series.* Hobart, Tasmania: Water and Marine Resources Division. Department of Primary Industries, Parks, Water and Environment.

DPIW 2007. *Environmental Flows for the South Esk Water Management Plan*. Water Assessment BranchWater, Resources Division, Department of Primary Industries and Water, Technical Report No. WA 07/01.

DPIW 2008a. *Conservation of Freshwater Ecosystem Values (CFEV) Project Technical Report*. Hobart, Tasmania: Conservation of Freshwater Ecosystem Values Program, Department of Primary Industries and Water.

DPIW 2008b. *Conservation of Freshwater Ecosystem Values (CFEV) Project Technical Report: Appendices.* Hobart, Tasmania: Conservation of Freshwater Ecosystem Values Project, Department of Primary Industries and Water.

ELLISON, J., BESTER, C., ARKLEY, K., DELL, G., HOLLAND, S., CLARK, M., HANNAFORD, R., TAYLOR, E., ATKINS, C., FOSTER, I. & MORRISON, B. 2002. *Baseline survey of fluvial geomorphology and hydrology of Pipers River*. Report prepared for the Tamar Natural Resource Management Strategy. Hobart: University of Tasmania.

FERGUSON, R. 1987. Hydraulic and sedimentary controls of channel pattern. *River channels***,** 129-158.

FISHER, S. G., HEFFERNAN, J. B., SPONSELLER, R. A. & WELTER, J. R. 2007. Functional ecomorphology: Feedbacks between form and function in fluvial landscape ecosystems. *Geomorphology,* 89**,** 84-96.

FOTHERBY, L. M. 2009. Valley confinement as a factor of braided river pattern for the Platte River. *Geomorphology,* 103**,** 562-576.

FOX-HUGHES, P. 2009. A heavy rainfall event in Northern Tasmania during 27 to 30 January 2004. *Australian Meteorological and Oceanographic Journal* 58**,** 151-166.

FRISSELL, C. A., LISS, W. J., WARREN, C. E. & HURLEY, M. D. 1986. A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. *Environmental Management,* 10**,** 199-214.

GARNAUT, R. 2008. Garnaut climate change review: Interim report to the Commonwealth, state and territory governments of Australia. *Garnaut Climate Change Review*.

GAUGHWIN, D. 1992. Trade, capital and the development of the extractive industries of northeast Tasmania *Australasian historical archaeology* 10**,** 55-64.

GIPPEL, C. J. & STEWARDSON, M. J. 1998. Use of wetted perimeter in defining minimum environmental flows. *River Research and Applications,* 14**,** 53-67.

GURNELL, A., SURIAN, N. & ZANONI, L. 2009. Multi-thread river channels: A perspective on changing European alpine river systems. *Aquatic Sciences - Research Across Boundaries*.
GURNELL, A. M. & PETTS, G. E. 2002. Island-dominated landscapes of large floodplain rivers, a European perspective. *Freshwater Biology,* 47**,** 581-600.
HARDIE, S. A., BOBBI, C. J. & BARMUTA, L. A. 2012. Macroinvertebrate and water quality responses to low flows in Tasmanian rivers. *Low flows report series.* Canberra: National Water Commission.
HART, B. T. & POLLINO, C. A. 2009. *Bayesian modelling for risk-based environmental water allocation,* Canberra, National Water Commission.
HARVEY, G. L., GURNELL, A. M. & CLIFFORD, N. J. 2008. Characterisation of river reaches: The influence of rock type. *CATENA,* 76**,** 78-88.
HERITAGE, G. L., BROADHURST, L. J., VAN NIEKERK, A. W., ROGERS, K. H. & MOON, B. P. 2000. The definition and characterisation of representative reaches for river management. Johannesburg: Centre for Water in the Environment, University of the Witwatersrand.
HOUSHOLD, I. 1999. Appendix 1. Fluvial geomorphology of the Lake River system. *In:* WOOLLEY, A. (ed.) *Riparian vegetation and bank condition along a section of the Lake River in Northern Tasmania.* Hobart: Bushcare.
HOWARD, A. D. 1987. Modelling fluvial systems: rock-, gravel- and sand-bed channels. *River channels***,** 69-94.
HUGHES, J. M. R. 1987. Hydrological Characteristics and Classification of Tasmanian Rivers. *Australian Geographical Studies,* 25**,** 61-82.
JAIN, V., FRYIRS, K. & BRIERLEY, G. 2008. Where do floodplains begin? The role of total stream power and longitudinal profile form on floodplain initiation processes. *Bulletin of the Geological Society of America,* 120**,** 127-141.
JERIE, K., I., H. & PETERS, D. 2003. *Tasmania's river geomorphology : stream character and regional analysis* Hobart, Nature Conservation Branch, Dept. of Primary Industries, Water and Environment.
JURACEK, K. E. & FITZPATRICK, F. A. 2003. Limitations and implications of stream classification. *Journal of the American Water Resources Association,* 39**,** 659-670.
KARR, J. R. 1999. Defining and measuring river health. *Fresh Water Biology,* 41**,** 221-234.
KELLERHALS, R., CHURCH, M. & BRAY, D. I. 1976. Classification and analysis of river processes. *Journal of the Hydraulics Division-Asce,* 102**,** 813-829.
KNIGHTON, A. D. 1987. Streamflow characteristics of northeastern Tasmania: I. regional flood flows. *Papers & Proceedings - Royal Society of Tasmania,* 121**,** 23-33.
KNIGHTON, A. D. 1989. River adjustment to changes in sediment load: the effects of tin mining on the Ringarooma River, Tasmania, 1875–1984. *Earth Surface Processes and Landforms,* 14**,** 333-359.
KNIGHTON, A. D. 1991. Channel bed adjustment along mine-affected rivers of northeast Tasmania. *Geomorphology,* 4**,** 205-219.
KNIGHTON, A. D. 1999. The gravel-sand transition in a disturbed catchment. *Geomorphology,* 27**,** 325-341.
KNIGHTON, A. D. & NANSON, G. C. 1993. Anastomosis and the continuum of channel pattern. *Earth Surface Processes and Landforms,* 18**,** 613-625.
KNIGHTON, D. 1998. *Fluvial Forms and Processes: A new perspective,* London, Arnold.
KONDOLF, G. M. 1995. Geomorphological stream channel classification in aquatic habitat restoration: Uses and limitations. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 5**,** 127-141.
KONDOLF, G. M., MONTGOMERY, D. R., PIEGAY, H. & SCHMITT, L. 2003. Geomorphic classification of rivers and streams. *In:* KONDOLF, G. M. & PIEGAY, H. (eds.) *Tools in Fluvial Geomorphology.* Chichester: John Wiley and Sons.
LADSON, A. R., WHITE, L. J., DOOLAN, J. A., FINLAYSON, B. L., HART, B. T., LAKE, P. S. & TILLEARD, J. W. 1999. Development and testing of an Index of Stream Condition for waterway management in Australia. *Fresh Water Biology,* 41**,** 453-468.
LEOPOLD, L. B. & WOLMAN, M. G. 1957. River channel patterns; braided meandering, and straight. Reston, VA, USA.

LOCATELLI, A. 2001. *Fluvial Geomorphology of the Pipers River, North East Tasmania.* University of Tasmania.
LOUGH, J. M. & HOBDAY, A. J. 2011. Observed climate change in Australian marine and freshwater environments. *Marine and Freshwater Research,* 62**,** 984-999.
MADDOCK, I. 1999. The importance of physical habitat assessment for evaluating river health. *Freshwater Biology,* 41**,** 373-391.
MARREN, P. M., MCCARTHY, T. S., TOOTH, S., BRANDT, D., STACEY, G. G., LEONG, A. & SPOTTISWOODE, B. 2006. A comparison of mud- and sand-dominated meanders in a downstream coarsening reach of the mixed bedrock-alluvial Klip River, eastern Free State, South Africa. *Sedimentary Geology,* 190**,** 213-226.
MARSTON, R. A., GIREL, J., PAUTOU, G., PIEGAY, H., BRAVARD, J. P. & ARNESON, C. 1995. Channel metamorphosis, floodplain disturbance and vegetation development - Ain River, France. *Geomorphology,* 13**,** 121-131.
MCCONACHY, F., XUEREB, K., SMYTHE, C. & GAMBLE, S. 2003. Homogeneity of Rare to Extreme Rainfalls over Tasmania. *In:* BOYD, M., BALL, J., BABISTER, M. & GREEN, J. (eds.) *28th International Hydrology and Water Resources Symposium: About Water.* Wollongong, N.S.W.: Institution of Engineers, Australia.
MCINTOSH, P. D., PRICE, D. M., EBERHARD, R. & SLEE, A. J. 2009. Late Quaternary erosion events in lowland and mid-altitude Tasmania in relation to climate change and first human arrival. *Quaternary Science Reviews,* 28**,** 850-872.
MILLER, J. R., RITTER, D. F. & KOCHEL, R. C. 1990. Morphometric assessment of lithologic controls on drainage basin evolution in the Crawford Upland, south-central Indiana. *American Journal of Science,* 290**,** 569-599.
MONTGOMERY, D. R. 1999. Process domains and the river continuum. *JAWRA Journal of the American Water Resources Association,* 35**,** 397-410.
MONTGOMERY, D. R. & BUFFINGTON, J. M. 1997. Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin,* 109**,** 596-611.
NAIMAN, R. J., BECHTOLD, J. S., DRAKE, D. C., LATTERELL, J. J., O'KEEFE, T. C. & BALIAN, E. V. 2005. Origins, Patterns, and Importance of Heterogeneity in Riparian Systems. *Ecosystem Function in Heterogeneous Landscapes.*
NAIMAN, R. J., LONZARICH, D. G., BEECHIE, T. J. & RALPH, S. C. 1992. General principles of classification and the assessment of conservation potential in rivers. *River conservation and management***,** 93-123.
NANSON, G. C. & BARBETTITAYLOR, M. G. 1995. River stabilization due to changing climate and vegetation during the late Quaternary in western Tasmania, Australia. *Geomorphology,* 13**,** 145-158.
NANSON, G. C. & KNIGHTON, A. D. 1996. Anabranching rivers: their cause, character and classification. *Earth Surface Processes and Landforms,* 21**,** 217-239.
NANSON, G. C., PRICE, D. M., JONES, B. G., MAROULIS, J. C., COLEMAN, M., BOWMAN, H., COHEN, T. J., PIETSCH, T. J. & LARSEN, J. R. 2008. Alluvial evidence for major climate and flow regime changes during the middle and late Quaternary in eastern central Australia. *Geomorphology,* 101**,** 109-129.
NANSON, G. C., PRICE, D. M. & SHORT, S. A. 1992. Wetting and drying of Australia over the past 300 ka. *Geology,* 20**,** 791-794.
NEWSON, M. D., CLARK, M. J., SEAR, D. A. & BROOKES, A. 1998. The geomorphological basis for classifying rivers. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 8**,** 415-430.
NRM SOUTH 2009. Tasmanian River Condition Index Reference Manual. Hobart: NRM South.
NWC 2011. The National Water Initiative-securing Australia's water future: 2011 assessment. Canberra: National Water Commision.
NWC 2013. Strategic Plan 2013-16 Canberra: National Water Commission.
PARSONS, M., MCLOUGHLIN, C. A., ROUNTREE, M. W. & ROGERS, K. H. 2006. The biotic and abiotic legacy of a large infrequent flood disturbance in the Sabie River, South Africa. *River Research and Applications,* 22**,** 187-201.
PHILLIPS, J. D. 2008. Geomorphic controls and transition zones in the lower Sabine River. *Hydrological Processes,* 22**,** 2424-2437.

PHILLIPS, J. D. & SLATTERY, M. C. 2008. Antecedent alluvial morphology and sea-level controls on form-process transition zones in the lower Trinity River, Texas. *River Research and Applications,* 24**,** 293-309.
POFF, N. L., ALLAN, J. D., BAIN, M. B., KARR, J. R. & ET AL. 1997. The natural flow regime. *BioScience,* 47**,** 769-784.
POFF, N. L., RICHTER, B. D., ARTHINGTON, A. H., BUNN, S. E., NAIMAN, R. J., KENDY, E., ACREMAN, M., APSE, C., BLEDSOE, B. P., FREEMAN, M. C., HENRIKSEN, J., JACOBSON, R. B., KENNEN, J. G., MERRITT, D. M., O'KEEFFE, J. H., OLDEN, J. D., ROGERS, K., THARME, R. E. & WARNER, A. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology,* 55**,** 147-170.
POOLE, G. C. Fluvial landscape ecology: addressing uniqueness within the river discontinuum. 2002. Blackwell Publishing Ltd, 641-660.
POST, D., CHIEW, F., TENG, J., VINEY, N., LING, F., HARRINGTON, G., CROSBIE, R., GRAHAM, B., MARVANEK, S. & MCLOUGHLIN, R. 2012. A robust methodology for conducting large-scale assessments of current and future water availability and use: a case study in Tasmania, Australia. *Journal of Hydrology,* 412**,** 233-245.
REINFELDS, I., HAEUSLER, T., BROOKS, A. J. & WILLIAMS, S. 2004. Refinement of the wetted perimeter breakpoint method for setting cease-to-pump limits or minimum environmental flows. *River Research and Applications,* 20**,** 671-685.
RENSCHLER, C. S., DOYLE, M. W. & THOMS, M. 2007. Geomorphology and ecosystems: Challenges and keys for success in bridging disciplines. *Geomorphology,* 89**,** 1-8.
RICE, S. P., FERGUSON, R. I. & HOEY, T. B. 2006. Tributary control of physical heterogeneity and biological diversity at river confluences. *Canadian Journal of Fisheries and Aquatic Sciences,* 63**,** 2553-2566.
ROSGEN, D. L. 1994. A classification of natural rivers. *CATENA,* 22**,** 169-199.
SCHMITT, L., MAIRE, G., NOBELIS, P. & HUMBERT, J. 2007. Quantitative morphodynamic typology of rivers: a methodological study based on the French Upper Rhine basin. *Earth Surface Processes and Landforms,* 32**,** 1726-1746.
SCHOLL, F. & HAYBACH, A. 2004. Topology of large European rivers according to their Chironomidae communities (Insecta : Diptera). *Annales de Limnologie,* 40**,** 309-316.
SCHUMM, S. A. 1977. *The Fluvial System,* New York, John Wiley.
SHARPLES, C. 1996. The geology and landforms of northeast Tasmania.
SIMON, A., DOYLE, M., KONDOLF, M., SHIELDS, F. D., RHOADS, B. & MCPHILLIPS, M. 2007. Critical evaluation of how the Rosgen classification and associated "natural channel design" methods fail to integrate and quantify fluvial processes and channel response. *Journal of the American Water Resources Association,* 43**,** 1117-1131.
SIMPSON, C. J. & SMITH, D. G. 2001. The braided Milk River, Northern Montana, fails the Leopold-Wolman discharge-gradient test. *Geomorphology,* 41**,** 337-353.
SKIRVING, W. J. 1989. *Suspended Sediment Transport in the North Esk River.* MSc thesis

(hard bound: 2 copies), University of Tasmania (Geography).
SMAKHTIN, V. U. 2001. Low flow hydrology: a review. *Journal of Hydrology,* 240**,** 147-186.
SMITH, G. H. S. & FERGUSON, R. I. 1995. The gravel sand transition along river channels. *Journal of Sedimentary Research Section a-Sedimentary Petrology and Processes,* 65**,** 423-430.
SNELDER, T. H. & BIGGS, B. J. 2002. Multiscale river environment classification for water resources management. *Journal of the American Water Resources Association,* 38**,** 1225-1239.
SOUTH, N. 2009. TRCI Physical Form Field Manual. Hobart: NRM Soiuth.
TADAKI, M., BRIERLEY, G. & Cullum, C. 2014. River classification: theory, practice, politics. *WIREs Water,* 1, 349-367.
THOMPSON, C. & CROKE, J. 2008. Channel flow competence and sediment transport in upland streams in southeast Australia. *Earth Surface Processes and Landforms,* 33**,** 329-352.
THOMSON, J. R., TAYLOR, M. P. & BRIERLEY, G. J. 2004. Are River Styles ecologically meaningful? A test of the ecological significance of a geomorphic river characterization scheme. *Aquatic Conservation-Marine and Freshwater Ecosystems,* 14**,** 25-48.

THORN, C. E. 1988. An introduction to theoretical geomorphology.
TINKLER, K. J. 1985. *A Short History of Geomorphology,* Totowa, New Jersey, Barnes and Noble Books.
URBAN, M. A. & DANIELS, M. 2006. Introduction: Exploring the links between geomorphology and ecology. *Geomorphology,* 77**,** 203-206.
VILES, H. A., NAYLOR, L. A., CARTER, N. E. A. & CHAPUT, D. 2008. Biogeomorphological disturbance regimes: progress in linking ecological and geomorphological systems. *Earth Surface Processes and Landforms,* 33**,** 1419-1435.
VÖRÖSMARTY, C. J., MCINTYRE, P. B., GESSNER, M. O., DUDGEON, D., PRUSEVICH, A., GREEN, P., GLIDDEN, S., BUNN, S. E., SULLIVAN, C. A., LIERMANN, C. R. & DAVIES, P. M. 2010. Global threats to human water security and river biodiversity. *Nature,* 467**,** 555-61.
WALLIS, E., MAC NALLY, R. & LAKE, P. S. 2008. A Bayesian analysis of physical habitat changes at tributary confluences in cobble-bed upland streams of the Acheron River basin, Australia. *Water Resources Research,* 44**,** 10.
WELSH, H. H. 2011. Frogs, fish and forestry: An integrated watershed network paradigm conserves biodiversity and ecological services. *Diversity,* 3**,** 503-530.
WIPFLI, M. S., RICHARDSON, J. S. & NAIMAN, R. J. 2007. Ecological Linkages Between Headwaters and Downstream Ecosystems: Transport of Organic Matter, Invertebrates, and Wood Down Headwater Channels¹. *JAWRA Journal of the American Water Resources Association,* 43**,** 72-85.
WOHL, E. & LEGLEITER, CARLÂ J. 2003. Controls on Pool Characteristics along a Resistantant Boundary Channel. *The Journal of Geology,* 111**,** 103-114.
ZAVADIL, E. A. 2009. *On the geomorphic criteria underpinning spatial scale hierarchies in river research and management.* PhD, The University of Melbourne.

Chapter 2 Magnitude Frequency Analysis of Small Floods Using the Annual and Partial Series

Abstract: Flood frequency analysis using partial series data has been shown to provide better estimates of small to medium magnitude flood events than the annual series, but the annual series is more often employed due to its practicality. Where partial series average recurrence intervals are required, annual series values are often "converted" to partial series values using the Langbein equation, regardless of whether the statistical assumptions behind the equation are fulfilled. This study uses data from Northern Tasmanian stream-gauging stations to make empirical comparisons between annual series and partial flood frequency estimates and values provided by the Langbein equation. At T = 1.1 years annual series estimates were found to be one third the magnitude of partial series estimates, while Langbein adjusted estimates were three quarters the magnitude of partial series estimates. The three methods converged as average recurrence interval increased until there was no significant difference between the different methods at T = 5 years. These results suggest that while the Langbein equation reduces the differences between the quantile estimates of annual maxima derived from annual maxima series and partial duration series flood frequency estimates, it does not provide a suitable alternative method to using partial series data. These results have significance for the practical estimation of the magnitude-frequency of small floods.

2.1. Introduction

Estimates of the size and frequency of floods is important for infrastructure planning and design and in the management of water resources and riparian areas (National Flood Risk Advisory Group, 2008). Research on flood frequency has focused largely on the estimation of extreme flood events, rather than the more frequent small to moderate magnitude flood events. However the frequency of small to moderate magnitude flood events are also of interest to geomorphologists and others, as discharge events of varying magnitude, frequency and temporal structure influence river channel form (Wolman and Miller (1960).

Extreme flood events may substantially modify the river channel but occur rarely while smaller discharges which may have little ability to modify the river channel individually, have a magnified contribution due to their high frequency. The most geomorphically effective flow in alluvial rivers has been the subject of considerable debate (e.g. Leopold et al., 1964, Armstrong et al., 2012) (See Section 1.3).

Secondly, the discharge which occurs at bankfull stage has been linked to channel formation. In a highly influential work, Wolman and Miller (1960) suggested that while discharge events of varying magnitude, frequency and temporal structure influence channel form, the channel morphology of meandering rivers appears to be associated with flows at or near the bankfull stage. The correlation between channel shape and bankfull discharge has since been widely debated (Pickup and Warner, 1976, Simon et al., 2004), but ideas of a channel forming discharge to which the channel geometry becomes adjusted continue to be central to fluvial geomorphology studies (Doyle et al., 2007).

The Institution of Engineers Australia (IEA) recommends the use of the partial series for estimating the magnitude-frequency of frequent floods (Institution of Engineers Australia, 1987), as it has been shown to provide more accurate estimates of frequent flood events than the annual series (Institution of Engineers Australia, 1987, Armstrong et al., 2012). However, the partial series is seldom used due to uncertainty in its application (Page and McElroy, 1981, Madsen et al., 1997, Lang et al., 1999), with decisions related to ensuring the independence of each flood event, a prerequisite to any statistical frequency analysis, being of particular difficulty (Lang et al., 1999). Instead, the magnitude of frequent flood events is commonly determined by transforming annual series estimates using a formula known as the Langbein equation. Recognising the theoretical statistical relationships that exist between the annual and partial series under certain criteria, Langbein (1949) demonstrated a method for converting annual series average recurrence intervals to partial series intervals. Originally developed for use in specific statistical situations, the Langbein equation has subsequently been commonly used as a practical method to convert annual series intervals to partial series intervals, even when the statistical assumptions behind the equation are not met (Dalrymple, 1960, Woodyer, 1966, Page and McElroy, 1981, Perica et al., 2011, Bezak et al., 2013, Gottschalk et al., 2013).

2.1.1. Flood Frequency Analysis

Flood frequency analysis is used for making probabilistic estimates of a future flood event based on the historical streamflow record. The probability of a flood event occurring is often expressed as the average length of time between floods and called the return period or average recurrence interval (*T*), although the probability of flood events can also be expressed using Annual Exceedance Probability (AEP), which is the probability of an event occurring or being exceeded within a year (See Appendix 2.1). The two main methods of flood frequency analysis are analytical and graphical, with the IEA (Institution of Engineers Australia, 1987) recommending that both procedures are used in a complementary manner. The analytical method of flood frequency analysis usually involves fitting a probability distribution function to model the observed peak flow data from which the probability of exceedance of flow-discharge of a particular magnitude flood may then be calculated. Although this method is widely used, there is little theoretical basis in the choice of distribution (Cunnane, 1985, Kidson and Richards, 2005), and despite extensive research, no particular distribution has emerged as the best fitted across and most uniform across different sites (Adamowski et al., 1998). The parameters of the probability distribution are generally estimated through analysis of the selected data sample, which is assumed to be representative of its parent population. Methods such as L-moment diagrams and associated goodness-of-fit procedures have been advocated for evaluating the suitability of various distributional alternatives for modeling flood flows in a region (Vogel et al., 1993). However, the true distribution and its parameters may still differ significantly from the empirically fitted distribution, particularly when samples are small (Singh and Strupczewski, 2002).

Of the two main choices of data series in flood frequency analysis, the most frequently used is the annual series, which is composed of the single maximum discharge for each year of the record. IEA (Institution of Engineers Australia, 1987) identified three advantages to using the annual series: there is a high probability that flood events are independent; the series is easily and unambiguously extracted; and the form of the frequency distribution of annual floods generally conform to theoretical distributions. The major disadvantage to using the annual series is that because only one flood is included from each year of the streamflow record, the annual series may exclude significantly large floods if several occur in a single year and may include small annual maximums for some years. This may result in small floods occurring more frequently than indicated by the annual series (Armstrong et al., 2012).

The partial series, also known as Peaks Over Threshold (POT), is composed of all discharges over a chosen threshold for the entire stream gauge record—some years may contribute several floods and other years none. Advantages of the partial series are that insignificant floods are excluded, which can improve magnitude estimates of high frequency floods (Armstrong et al., 2012), and that the partial series can produce more data points than the annual series, which can be particularly useful when the period of streamflow record is short (Institution of Engineers Australia, 1987). However, historically the partial series has been less commonly used than the annual series, mainly due to the complexity in choosing the threshold discharge level and ensuring the independence of each flood event (Madsen et al., 1997, Lang et al., 1999, Navratil et al., 2006, Mohssen, 2009, Rahman et al., 2013). As there is no unique threshold value which best defines the partial series (Beguería, 2005), an appropriate level must be determined, generally through the trial of several different threshold levels (Lang et al., 1999, Kidson and Richards, 2005, Mohssen, 2009). Lowering the threshold up to a certain level increases the number of data points which may improve flood frequency estimates. However as the number of flood events in the series increases, the possibility that they will not be independent also increases, as conditions created by one flood may also affect following floods (e.g., soil moisture). No general guidelines for ensuring independence have been developed, with the criterion for independence instead requiring subjective judgment, with consideration of the circumstances and objectives of the study and the characteristics of the catchment and flood data (Institution of Engineers Australia, 1987).

2.1.2. Low Magnitude Frequent Floods

Due to the difficulties in defining the partial series, the estimation of the magnitude-frequency of frequent floods is often made using the easier to define annual series, despite evidence it underestimates their magnitude (Armstrong et al., 2012). The annual series also provides a different measure of the probability of a flood, the average recurrence interval, to that provided by the partial series. As the annual series only considers one flood for each year, the average recurrence interval in this series is the average interval of time in which a flood of the selected magnitude occurs as an annual maximum, whereas the average recurrence interval for the partial series is the average time interval between two successive floods of at least the selected magnitude (Woodyer, 1966).

Assuming that the floods in the partial series are independent and distributed according to a Poisson process, Langbein (1949) demonstrated the existence of a statistical relationship between the recurrence intervals generated by the two series. This relationship between the two series was further defined by Chow (1950) to produce the equation:

$$T_P = \frac{1}{\ln T_A - \ln (T_A - 1)} \qquad (2.1)$$

where T_P is the average recurrence interval determined for the partial series and T_A is the corresponding average recurrence interval using the annual series. While other empirically derived relationships between the annual and partial series have been produced for particular datasets ranging from 20 to 46 years (Beran and Nozdryn-Plotnicki, 1977, Mohssen, 2009), a more common approach has been to use the Langbein equation, or a table of equivalent annual and partial series values based on the Langbein equation (e.g. Woodyer, 1968, Dury, 1976, Chen, 1983, Frazier et al., 2003, Konrad et al., 2005, Rogers et al., 2009, Perica et al., 2011) to "convert" annual series flood frequency values to partial series values regardless of the theoretical validity of it application. Several studies have shown significant deviations from the values predicted by the equation when using empirical data (Langbein, 1949, Page and McElroy, 1981, Takeuchi, 1984), with differences between actual recurrence intervals and those predicted by the Langbein equation up to 40 percent for floods of relatively high frequency at some locations (Page and McElroy, 1981).

The objective of this paper is to compare magnitude-frequency estimates of frequent floods determined using the annual series, the Langbein adjusted annual series and the partial series, and to determine whether Langbein's equation provides a suitable empirical method to convert annual series flood frequency average return intervals to partial series intervals. The purpose of this study is to improve understanding of practical methods available to fluvial geomorphologists and catchment managers for the estimation of high-frequency low-magnitude flood events. This would allow estimation of the frequency or magnitude of geomorphically important flood events such as bankfull discharge.

2.2. Methods

2.2.1. Study Area

Tasmania is the southernmost state in Australia, with the main island extending across a latitudinal range of 39°40′–43°20′ S. The North-eastern region covers almost one-third of Tasmania’s landmass (Figure 1), and is delineated by the Tamar Estuary in the West and the Fingal Valley in the South. The region’s temperate marine climate includes a winter dominated rainfall that is largely controlled by topography and ranges from an annual average of less than 700 mm in low lying and coastal areas up to more than 1200 mm in the highlands (Bureau of Meteorology, 1993). Steep precipitation gradients exist in some areas, and occasional very heavy rainfall events associated with the passage of intense low pressure systems occur about some areas of the region causing localised flooding (Fox-Hughes, 2009).

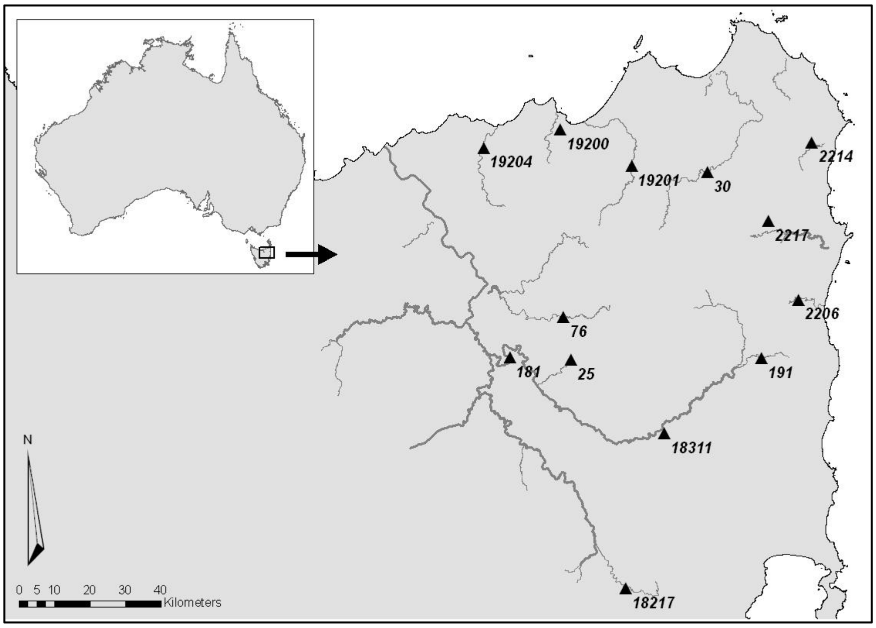
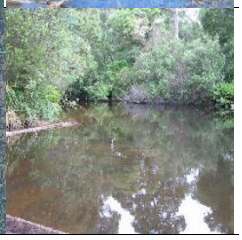


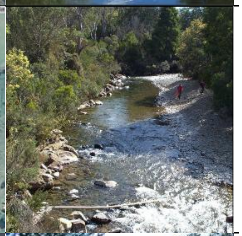
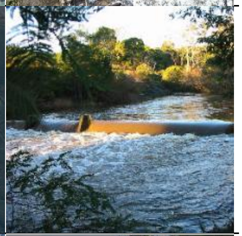
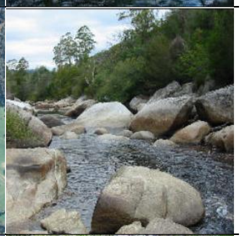
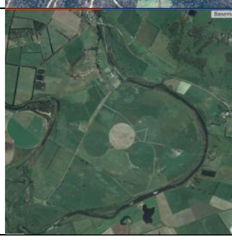
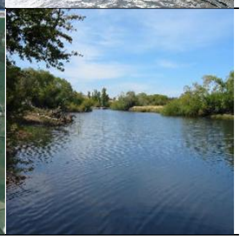
Figure 2.1. Location of major rivers and streamflow stations in north-eastern Tasmania used in this study. State Government stream-gauge codes are used to identify sites.

2.2.2. Data

Stream-flow data for the thirteen gauging stations shown in Figure 2.1 and listed in Table 2.1 were obtained from the Tasmanian Department of Primary Industries, Parks, Water and the Environment (DPIPWE). These DPIPWE stations represent all those in north-eastern Tasmania that possess records of adequate quality and at least 10 years of data, which was identified as the minimum sample length for flood frequency analysis (Adamowski and Feluch, 1990). Obvious errors were removed from the streamflow data and only years with full hydrological data were included. No infilling of missing data was attempted. Regardless of the size of catchment, topography, size and land cover, the original 15 minute sampling period data was transformed to a daily time step by calculating the mean discharge for each 24 hour period of record. The gauging stations are distributed throughout north-eastern Tasmania (Figure 2.1) on a variety of stream types, and have accumulated catchment areas ranging from 26.4 km^2 to 3306.4 km^2, with a mean of 509.5 km^2. The number of years of streamflow record (n) varied significantly around the mean of 33 years, with the maximum length being 85 years (North Esk River at Ballroom) and three sites having the minimum length of 10 years (Ansons River downstream of Big Boggy Creek, Nile River at Deddington and Scamander River upstream of Scamander water intake).

Table 2.1. Stream gauging sites and flow records used in the flood frequency analyses.

Site Code	**Site Name**	**Years of Record (n)**	**Catch Area (km^2)**	**River Style**	**Images[1]**	
2214	Ansons River downstream of Big Boggy Creek	10	228.9	Confined		
191	Break O'Day River at Killymoon	28	186.2	Unconfined		
19200	Brid River 2.6 km upstream of tidal limit	34	138.9	Unconfined		
19201	Great Forester River 2 km upstream of Forester Road	41	192.0	Unconfined		

18217	Macquarie River at Trefusis	32	375.3	Partially Confined		
76	North Esk River at Ballroom	85	375.9	Partially Confined		
25	Nile River at Deddington	10	220.9	Partially Confined		
19204	Pipers River downstream of Yarrow Creek	39	298.4	Partially Confined		
30	Ringarooma River upstream of Moorina Bridge	34	482.3	Confined		
2217	Ransom River at Sweet Hills	28	26.4	Partially Confined		
2206	Scamander River upstream Scamander water intake	10	268.0	Partially Confined		
181	South Esk River above Macquarie River	55	3306.4	Unconfined		

18311	St. Pauls River upstream of South Esk River	23	524.2	Unconfined		

Note: years of record relates to the period immediately prior to 1 January 2012.
[1]. Satellite images sourced from The List (http://maps.thelist.tas.gov.au/listmap/app/list/map); Site photographs sourced from WIST (http://wrt.tas.gov.au/wist).

2.2.3. Annual Series

Daily streamflow data from each site was time-stepped to annual maxima, with checks made to ensure peak events from one year were not included as peak events for the following year. While there are various a-priori theories for choosing particular probability distributions for flood frequency data, in practical applications empirical suitability plays a much larger role in distribution choice (Cunnane, 1985, Kidson and Richards, 2005). In a study of the suitability of a range of distributions using a large set of Australian annual series data, Rahman et al. (2013) recommended that the Log-Pearson 3, Generalized Extreme Value, and Generalized Pareto Distributions should be compared before the final choice of a distribution. In this study a single distribution was used, with the choice based on previously demonstrated empirical suitability as well as practicality. A two- parameter Log-Normal distribution with Bayesian Markov Chain Monte Carlo (BMCMC) parameter estimation has previously been found to be the best performing flood frequency distribution and associated parameter estimation procedure for Tasmanian annual series flood data (Haddad and Rahman, 2011). Hence this was used in this study, utilizing facilitating software (Viglione, 2009), with each algorithm iterated 5000 times. The fit of each Log-Normal distribution was checked visually using histograms and quantile–quantile (QQ) plots and the fitted distributions were also verified against the original data on log-log plots. Each distribution was also visually checked for outliers. Plotting positions for the observed peak discharges were determined following the general recommendations of Cunnane (1978) and IEA (Institution of Engineers Australia, 1987) using the equation:

$$T = \frac{[(n+1) - 2 \propto]}{(m - \propto)} \qquad (2.2)$$

where m is the rank of each event and α is a bias constant. The bias constant adjusts plotting positions to account for the dataset being a sample of the real population. The bias constant was set at 0.4 in this study following the example of previous flood frequency analysis studies in Eastern Australia (Rustomji, 2009). It should be noted that although censoring of the left hand tail flows of the distributions (i.e. those flows of lowest average recurrence interval) may have provided better distribution fits and discharge estimates that are closer to estimates made using the partial series in some cases, such censoring was not undertaken due to the small size of a number of the data sets.

2.2.4. Partial Series

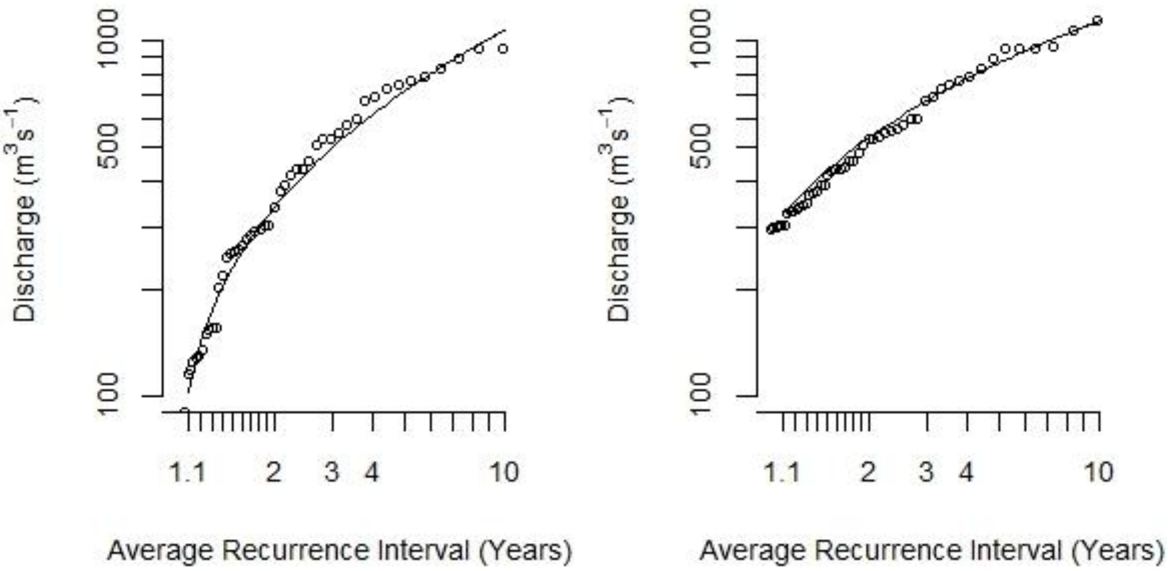
A peaks-over-threshold (POT) analysis was undertaken on daily streamflow data from each site (Haddad and Rahman, 2011). Ensuring the independence of successive flood peaks in the partial series is a complex and possibly subjective problem with no definitive guidelines existing (Lang et al., 1999). Malamud and Turcotte (2006) found relatively robust flood-frequency estimations using time intervals from 7 to 60 days between successive peaks, and Svensson *et al*. (2005) used thresholds depending on catchment size: 5 days for catchments <45,000 km^2, 10 days for catchments 45,000–100,000 km^2, and 20 days for catchments >100,000 km^2. As the largest catchment in this study was 3306 km^2 14 days between flood events was used as a criterion to ensure independence. In consideration of the range of values suggested by the literature, four different partial series were defined for each site. Thresholds were adjusted to provide partial series data sets where the number of events (k) equals 1n, 1.5n, 2n and 2.5n (named PS_1, $PS_{1.5}$, PS_2 and $PS_{2.5}$ respectively). The IEA (Institution of Engineers Australia, 1987) suggest that graphical interpolation is sufficiently accurate when using the partial series where T < 10 years, but that a probability distribution should be fitted for making inferences beyond this. Both analysis methods were used in this study. The Generalized Pareto Distribution (GPD) has been widely used for flood frequency analysis with partial series data (e.g. Madsen et al., 1997, Adamowski et al., 1998, Mohssen, 2009), and a three parameter GPD was fitted to each of the four partial series data sets for each of the thirteen sites in this study. The parameters of the GPD were estimated (Haddad and Rahman, 2011) using a maximum likelihood approach (Ribatet, 2011). Distributions were checked against the plotted streamflow data following the procedures outlined for the annual series above. The coefficient of variation (*CV*) of the grouped partial series estimates was also determined as a measure of their dispersion.

2.2.5. Comparison of Different Methods

At-site flood frequency estimates for T = 1.1, 1.5, 2, 3, 5 and 10 years were made for each of the 13 stations for both the annual series (AS) and for each of the four partial series (PS_1, $PS_{1.5}$, PS_2, $PS_{2.5}$) using the procedures detailed above. Langbein adjusted flood frequency estimates (LC) were determined from the annual series estimates using Equation (2.1). It should be noted that Langbein's equation is used in this study to determine if it provides an empirical method to convert annual series average recurrence intervals to partial series average recurrence intervals, and that consequently the theoretical assumptions behind the equation were not considered in the choice of flood frequency analysis method. The PS_1 values (also referred to as PS) were chosen for comparison with annual series estimates (*AS*) and Langbein adjusted annual series estimates (*LC*), as the data set on which the PS_1 estimates were based contained the same number of flood events as the annual series. In addition, all partial series magnitude estimates were generally closely clustered, irrelevant of the number of flood events included. The three estimates (*AS*, *PS* and *LC*) were then compared, and the ratio of *AS* to *PS* and *LC* to *PS* was calculated for each station. Mean ratios averaged across all thirteen stations were also compared.

2.3. Results

Data generally conformed well to statistical models, with both annual series and partial series at-site flood frequency curves created from the probability distributions providing a fairly good fit (Figure 2.2) with the observed data from each of the thirteen stream gauging stations. The generally good fit of the distributions to the data is demonstrated by results from the South Esk River above Macquarie River (Site 181) (Figure 2.2), with graphs of the fitted distributions against the observed data for both the annual and partial series for that site shown in Figure 2.2a and 2.2b respectively.



(**a**) (**b**)

Figure 2.2. Original streamflow data compared to fitted probability distributions (solid line) for the South Esk River above Macquarie River (Site 181); (a) annual series data against the Log-Normal distribution; and (b) partial series data against the Generalised Pareto Distribution.

Censoring of the left hand tail flows of the annual series distribution (i.e. the more frequent flows) may have provided better distribution fits and discharge estimates that are closer to estimates made using the partial series, however this would have resulted in datasets of inadequate length for flood frequency analysis (Adamowski and Feluch, 1990). The final partial and annual series flood frequency estimates are presented in Table 2, along with the coefficient of variation for the grouped partial series estimates (PS_1, $PS_{1.5}$, PS_2 and $PS_{2.5}$). Partial series *CV* was generally larger for sites with shorter streamflow records, and displayed a general increase at and above T = 5 years.

Table 2.2. Estimated discharge (m^3s^{-1}) for 1.1, 1.5, 2, 3, 4, 5 and 10 year average recurrence interval floods using partial (*PS*) and annual series (*AS*) data for Northern Tasmanian stream gauging stations (Coefficient of variation for partial series estimates shown in parentheses).

Site	Series	Average Recurrence Interval (years)						
		1.1	1.5	2	3	4	5	10
2214	*PS*	62.28	76.63	112.68	199.14	206.44	205.83	218.03
		(3.52)	(3.91)	(3.82)	(5.17)	(2.59)	(7.99)	(20.88)
	AS	7.10	26.09	48.37	90.66	125.60	156.90	292.55
191	*PS*	77.93	90.70	116.90	154.97	166.99	180.77	244.44
		(0.74)	(1.90)	(2.50)	(2.8)	(0.83)	(2.57)	(6.35)
	AS	14.92	40.89	67.07	107.87	142.52	173.00	287.26
19200	*PS*	10.01	11.30	12.21	14.00	15.11	16.14	20.21
		(0.93)	(1.50)	(1.50)	(1.60)	(0.69)	(0.67)	(3.69)
	AS	3.91	7.19	9.51	12.52	14.62	16.25	21.55
19201	*PS*	21.42	24.78	27.54	30.56	32.37	34.79	52.57
		(1.95)	(1.19)	(2.05)	(0.67)	(1.07)	(2.00)	(3.14)
	AS	10.72	17.63	22.26	28.43	32.53	35.61	45.94
18217	*PS*	63.24	72.44	85.20	102.55	112.18	120.62	173.35
		(1.28)	(0.52)	(1.89)	(1.33)	(0.54)	(1.79)	(1.01)
	AS	6.25	22.79	42.27	78.58	110.82	138.55	264.63
76	*PS*	51.41	59.53	66.48	73.36	77.68	80.60	92.67
		(1.86)	(1.21)	(2.35)	(0.90)	(0.37)	(1.13)	(1.95)
	AS	26.78	41.29	50.24	61.77	69.70	75.51	92.31
25	*PS*	68.62	79.06	93.89	108.64	109.11	109.33	111.01
		(2.30)	(0.83)	(2.69)	(1.38)	(2.38)	(4.93)	(10.47)
	AS	32.97	50.69	62.11	75.71	84.29	91.07	110.62
19204	*PS*	49.71	56.93	67.09	73.77	79.44	92.76	132.43
		(1.53)	(0.51)	(2.94)	(0.52)	(2.44)	(0.93)	(3.03)
	AS	18.46	35.77	49.40	68.38	82.17	92.24	129.21
30	*PS*	72.36	81.49	86.79	102.49	109.26	112.21	127.78
		(1.17)	(1.02)	(1.13)	(1.24)	(0.30)	(1.95)	(9.29)
	AS	43.01	65.86	79.92	97.30	108.25	117.08	145.20
2217	*PS*	4.53	5.31	7.09	9.45	11.25	12.80	20.28
		(0.93)	(1.71)	(2.93)	(1.72)	(0.48)	(1.16)	(1.43)
	AS	2.01	3.95	5.41	7.45	8.99	10.20	14.26
2206	*PS*	119.93	159.67	263.43	292.83	298.75	303.30	295.09
		(7.64)	(4.37)	(8.18)	(2.31)	(4.77)	(8.06)	(16.17)
	AS	9.50	39.97	79.52	157.04	228.05	298.17	601.73
181	*PS*	310.78	406.08	512.45	663.32	798.91	896.20	1162.37
		(3.34)	(1.10)	(3.08)	(1.38)	(0.84)	(0.73)	(7.12)
	AS	102.60	228.37	337.54	491.06	609.74	716.14	1069.25
18311	*PS*	106.63	144.54	165.07	207.46	284.52	334.64	419.42

	(4.11)	(3.14)	(1.65)	(2.39)	(1.75)	(1.98)	(6.91)
AS	20.94	59.48	95.28	152.71	198.40	240.11	394.74

The percentage differences between partial series (*PS*) and annual series estimates (*AS*) and between the partial series and Langbein adjusted annual series estimates (*LC*) averaged across all 13 sites are listed in Table 2.3. Differences were smallest at T = 5 years with Table 2.3 showing T = 5 results as closest to the ratio of 1, and increased as average recurrence interval decreased. *AS* estimates were 95 percent of *PS* estimates at T = 5 years but decreased to just 33 percent of *PS* estimates at T = 1.1 years. *LC* estimates were generally closer, ranging from 101 percent of *PS* estimates at T = 5 years to 75 percent of *PS* estimates at T = 1.1 years. Both *AS* and *LC* estimates were significantly larger than *PS* estimates at T = 10 years (119 and 122 percent respectively).

Table 2.3. Ratio of annual series estimates (*AS*) and Langbein adjusted annual series estimates (*LC*) to partial series (*PS*) estimates averaged across 13 north-eastern Tasmanian stream gauging stations.

Ratio	**Average Recurrence Interval (years)**						
	1.1	**1.5**	**2**	**3**	**4**	**5**	**10**
AS/PS	0.33	0.53	0.65	0.79	0.88	0.95	1.19
LC/PS	0.75	0.78	0.81	0.89	0.95	1.01	1.22

Figure 2.3 and Table 2.4 show mean annual series average recurrence intervals against the mean partial series recurrence interval at an equivalent discharge across the 13 north-eastern Tasmanian streamflow stations. Mean partial series discharge estimates at the lowest average recurrence interval (T = 1.1 years) were equivalent to a mean discharges on the annual series of 2.17 years average recurrence interval (*SD* = 0.33). Mean partial series estimates at T = 5 years were equivalent to T = 5.71 years on the annual series (*SD* = 1.00), and at T = 10 years partial series estimates were smaller than annual series estimates, with the equivalent annual series at T = 8.63 years (*SD* = 2.30).

Differences between mean Langbein adjusted annual series average recurrence intervals and partial series intervals were smaller than differences between annual series and partial series intervals, but remained significant at low average recurrence intervals. Mean partial series estimated discharge at T = 1.1 years were equivalent to a mean Langbein adjusted values at T = 1.67 years and at T = 5 years were equivalent to Langbein adjusted values at T = 5.52 years.

Table 2.4. Annual series average recurrence intervals (in years) equivalent to partial series as predicted by Langbein's function and estimated from mean values across 13 north-eastern Tasmanian streamflow stations.

Partial Series	Annual Series	
	Langbein function	North-eastern Tasmanian data
1.1	1.67	2.17
1.5	2.06	2.71
2.0	2.54	3.28
3.0	3.53	4.22
4.0	4.52	5.01
5.0	5.52	5.71
10.0	10.51	8.63

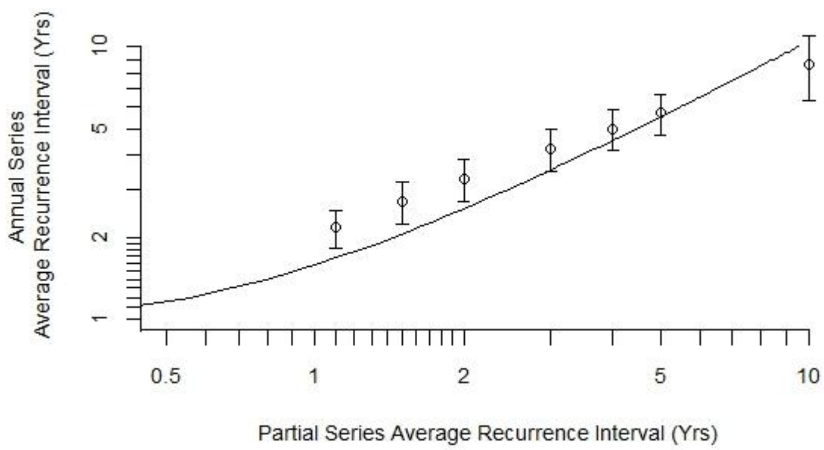


Figure 2.3. Comparison of annual and partial series average recurrence intervals (*T*). Conversion of annual series to partial series according to Langbein's function is represented by the solid line, while points represent mean (plus and minus standard deviation) of 13 north-eastern Tasmanian streamflow stations.

2.4. Discussion

Annual series flood frequency estimates made using data from Northern Tasmanian stream gauging stations differed from partial series estimates at most average recurrence intervals. Differences were largest for the most frequent floods, with annual series estimates only 33 percent of partial series estimates at $T = 1.1$ (Table 2.3). The difference between the two series progressively decreased as T increased until there was negligible difference at around $T = 5$ years (AS = 95% PS), and by $T = 10$ years annual series estimates were larger than partial series estimates (AS = 119% PS). These results coincide with those from other studies comparing annual and partial series estimates at low average recurrence intervals ($T < 10$ years). Langbein (1949) found that for equivalent floods, the recurrence intervals in the partial-duration series are smaller than in the annual series, and in results very similar to this study, also found that the difference between the two series is inconsequential for floods greater than about five year recurrence interval. Adamowski et al. (1998) also found annual series quantiles significantly less than partial series for frequent floods.

Differences between the two series reflect the different data sets used. The partial series, which uses all floods above a threshold, is likely to include more medium sized flood events than the annual series, which only uses the largest flood event of each year. As more flood events are included the average recurrence interval between peaks of a given magnitude automatically declines (Page and McElroy, 1981), and as a result small floods occur more frequently than indicated by the annual series (Armstrong et al., 2012). Differences between annual series and partial series estimates decrease for larger more infrequent floods because the majority of extreme flood events are likely to be included in both series.

The differences between Langbein adjusted values and partial series values reflect the differences between the annual and partial series. The largest differences between the two values occurred at the smallest average recurrence intervals, and decreased as T increased, until there was no significant difference between the two values at around T = 5 years (Table 2.4 and Figure 2.3). Langbein adjusted values (LC) averaged almost 40% lower magnitude discharge than partial series estimates at T = 1.1 years. The tendency for empirical results to deviate from the theoretical Langbein relationship has been previously demonstrated (Langbein, 1949, Beran and Nozdryn-Plotnicki, 1977, Page and McElroy, 1981, Takeuchi, 1984). The results from this study are very similar to results from Page and McElroy (1981), who found differences between actual recurrence intervals and those predicted by the Langbein equation to be as much as 40 percent for floods of relatively high frequency up to the level of the mean annual flood (assumed to be a flood with T = 2.33 years).

Previous studies (Langbein, 1949, Page and McElroy, 1981, Takeuchi, 1984) have attributed this difference to the difficulty in determining independent flood peaks for partial series. The Langbein function assumes that floods occur as statistically independent events, and because flood selection cannot always guarantee adherence to this it is unlikely that actual data will conform precisely with the mathematically derived function (Page and McElroy, 1981). This is not supported by the small differences in magnitude between partial series estimates made with varying thresholds in this study.

The variation between the different partial series estimates at a site was generally small at low average recurrence intervals (T < 5 years) in comparison to the difference between partial and annual series estimates, as illustrated by the small coefficient of variation values in Table 2. This suggests that the choice of threshold level has relatively little effect on partial series estimates at low recurrence intervals. Other authors (Institution of Engineers Australia, 1987, Armstrong et al., 2012) have recommended that the partial series be used to estimate floods with average recurrence intervals of around ten years or less, and the results from this study support those views, particularly for floods with an average recurrence interval of five years or less.

It should be noted that the revised edition of Australian Rainfall and Runoff (ARR), the national guideline document for the estimation of design flood characteristics in Australia published by Engineers Australia recommends the use of Annual Exceedance Probability (AEP) rather than average recurrence interval where practical (ARR, 2015). However average recurrence interval has been retained in this paper to reduce confusion, as the focus of this paper is largely on converting average recurrence intervals estimated using annual series flood data to average recurrence intervals estimated using partial series flood data. See Appendix 2.1 for further information.

2.5. Conclusion

This study found large differences between annual and partial series flood frequency estimates made using Northern Tasmanian streamflow data for average recurrence intervals of less than five years, similar to other studies finding such significant deviations (Langbein, 1949, Page and McElroy, 1981, Takeuchi, 1984). Annual series estimates were one third the magnitude of partial series estimates at T = 1.1 years, but the two series converged as average recurrence interval increased until there was no significant difference between the two series at T = 5 years. This study also found that at low recurrence intervals there were relatively small differences between the various partial series estimates for a site made using different discharge thresholds, especially in comparison to the differences between partial series and annual series flood frequency estimates. This suggests that the definition of the partial series data set may not be of critical importance at low average recurrence intervals, although more research is required to confirm this.

In addition, this study found that Langbein's equation did not provide a suitable empirical method to convert annual series flood frequency estimates to partial series estimates at average recurrence intervals of less than five years. Langbein adjusted annual series estimates were three quarters the magnitude of partial series estimates at $T = 1.1$ years.

These results suggest that both the annual series and the Langbein adjusted annual series significantly underestimate the magnitude of frequent floods and should not be used at average recurrence intervals of less than five years. Rather, the partial series should be used for estimates of high frequency-low magnitude floods ($T < 5$ years). While the high sampling variability associated with the small sample size in this study would be reduced by a larger survey, the results of this analysis are supported by those from other studies. As floods of this frequency are of interest to geomorphologists and ecologists, these results have particular significance for relevant research in these fields.

Appendix 2.1. Recurrence intervals and exceedance probability

This paper has expressed the probability of a flood event using the Average Recurrence Interval (ARI) rather than the Average Exceedance Probability (AEP). However it should be noted that:

"Use of the terms "recurrence interval" and "return period" has been criticised as leading to confusion in the minds of some decision makers and members of public. Although the terms are simple superficially, they are sometimes misinterpreted as implying that the associated magnitude is only exceeded at regular intervals, and that they are referring to the elapsed time to the next exceedance." (IEA, 1987).

Conversion of ARI to AEP can be conducted using the table below.

AEP (%)	AEP	ARI
99.75	1.002	0.17
98.17	1.02	0.25
95.02	1.05	0.33
86.47	1.16	0.50
63.21	1.58	1.00
50.00	2	1.44
39.35	2.54	2.00
20.00	5	4.48
18.13	5.52	5.00
10.00	10	9.49
5.00	20	20
2.00	50	50
1.00	100	100

References

ADAMOWSKI, K., & FELUCH, W. 1990. Nonparametric flood-frequency analysis with historical information. *Journal of Hydraulic Engineering,* 116**,** 1035-1047.

ADAMOWSKI, K., LIANG, G.-C. & PATRY, G. G. 1998. Annual maxima and partial duration flood series analysis by parametric and non-parametric methods. *Hydrological Processes,* 12**,** 1685-1699.

ARMSTRONG, W. H., COLLINS, M. J. & SNYDER, N. P. 2012. Increased Frequency of Low-Magnitude Floods in New England. *Journal of the American Water Resources Association,* 48**,** 306.

BEGUERÍA, S. 2005. Uncertainties in partial duration series modelling of extremes related to the choice of the threshold value. *Journal of Hydrology,* 303**,** 215-230.

BERAN, M. A. & NOZDRYN-PLOTNICKI, M. J. 1977. Estimation of low return period floods. *Hydrological Sciences Bulletin,* 22**,** 275-282.

BEZAK, N., BRILLY, M. & ŠRAJ, M. 2013. Comparison between the peaks over threshold method and the annual maximum method for flood frequency analyses. *Hydrological Sciences Journal*.

BUREAU OF METEOROLOGY 1993. *Climate of Tasmania,* Canberra, ACT, Australian Government Pub. Service.

CHEN, C. 1983. Rainfall Intensity-Duration-Frequency Formulas. *Journal of Hydraulic Engineering,* 109**,** 1603-1621.

CHOW, V. T. 1950. Discussion of *Annual floods and the partial duration flood series*. *Transactions American Geophysical Union,* 31**,** 939--941.

CUNNANE, C. 1978. Unbiased plotting positions — A review. *Journal of Hydrology,* 37**,** 205-222.

CUNNANE, C. 1985. Factors affecting choice of distribution for flood series. *Hydrological Sciences Journal,* 30**,** 25-36.

DALRYMPLE, T. 1960. Flood frequency analyses. Washington, USA: US Geological Survey Water-Supply Paper.

DURY, G. H. 1976. Discharge prediction, present and former, from channel dimensions. *Journal of Hydrology,* 30**,** 219-245.

FOX-HUGHES, P. 2009. A heavy rainfall event in Northern Tasmania during 27 to 30 January 2004. *Australian Meteorological and Oceanographic Journal* 58**,** 151-166.

FRAZIER, P., PAGE, K., LOUIS, J., BRIGGS, S. & ROBERTSON, A. I. 2003. Relating wetland inundation to river flow using Landsat TM data. *International Journal of Remote Sensing,* 24**,** 3755-3770.

GOTTSCHALK, L., YU, K.-X., LEBLOIS, E. & XIONG, L. 2013. Statistics of low flow: Theoretical derivation of the distribution of minimum streamflow series. *Journal of Hydrology,* 481**,** 204-219.

HADDAD, K. & RAHMAN, A. 2011. Selection of the best fit flood frequency distribution and parameter estimation procedure: A case study for Tasmania in Australia. *Stochastic Environmental Research and Risk Assessment,* 25**,** 415-428.

INSTITUTION OF ENGINEERS AUSTRALIA 1987. Australian Rainfall and Runoff: A Guide to Flood Estimation. Canberra.

KIDSON, R. & RICHARDS, K. S. 2005. Flood frequency analysis: assumptions and alternatives. *Progress in Physical Geography,* 29**,** 392-410.

KONRAD, C. P., BOOTH, D. B. & BURGES, S. J. 2005. Effects of urban development in the Puget Lowland, Washington, on interannual streamflow patterns: Consequences for channel form and streambed disturbance. *Water Resources Research,* 41**,** W07009.

LANG, M., OUARDA, T. B. & BOBEE, B. 1999. Towards operational guidelines for over-threshold modeling. *Journal of Hydrology,* 225**,** 103-117.

LANGBEIN, W. B. 1949. Annual Floods and the Partial-Duration Series. *Transactions American Geophysical Union,* 30**,** 879-881.

LEOPOLD, L. B., WOLMAN, G. M. & MILLER, J. P. 1964. *Fluvial Processes in Geomorphology,* San Francisco, W.H. Freeman and Co.

MADSEN, H., RASMUSSEN, P. F. & ROSBJERG, D. 1997. Comparison of annual maximum series and partial duration series methods for modeling extreme hydrologic events: 1. At-site modeling. *Water Resour. Res.,* 33**,** 747-757.

MALAMUD, B. D. & TURCOTTE, D. L. 2006. The applicability of power-law frequency statistics to floods. *Journal of Hydrology,* 322**,** 168-180.

MOHSSEN, M. Partial duration series in the annual domain. *In:* ANDERSSEN, R., BRADDOCK, R. & NEWHAM, L., eds. 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation, 2009 Cairns, Australia. Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation.

NATIONAL FLOOD RISK ADVISORY GROUP 2008. Flood Risk Management in Australia. *Australian Journal of Emergency Management, The,* 23**,** 21-27.

NAVRATIL, O., ALBERT, M. B., HÉROUIN, E. & GRESILLON, J. M. 2006. Determination of bankfull discharge magnitude and frequency: comparison of methods on 16 gravel-bed river reaches. *Earth Surface Processes and Landforms,* 31**,** 1345-1363.

PAGE, K. J. & MCELROY, L. 1981. Comparison of annual and partial duration series floods on the Murrumbidgee River. *Journal of the American Water Resources Association,* 17**,** 286-289.

PERICA, S., DIETZ, S., HEIM, S., HINER, L., MAITARIA, K., MARTIN, D., PAVLOVIC, S., ROY, I., TRYPALUK, C., UNRUH, D., YAN, F., YEKTA, M., ZHAO, T., BONNIN, G., BREWER, D., CHEN, L.-C., PARZYBOK, T. & YARCHOAN, J. 2011. NOAA Atlas 14 Volume 6 Version 2.0, Precipitation-Frequency Atlas of the United States, California. Silver Spring, MD: NOAA, National Weather Service.

RAHMAN, A. S., RAHMAN, A., ZAMAN, M. A., HADDAD, K., AHSAN, A. & IMTEAZ, M. 2013. A study on selection of probability distributions for at-site flood frequency analysis in Australia. *Natural Hazards***,** 1-11.

RIBATET, M. 2011. A User's Guide to the POT Package. Version 1.4 ed.

ROGERS, J. S., POTTER, K. W., HOFFMAN, A. R., HOOPES, J. A., WU, C. H. & ARMSTRONG, D. E. 2009. Hydrologic and Water Quality Functions of a Disturbed Wetland in an Agricultural Setting. *JAWRA Journal of the American Water Resources Association,* 45**,** 628-640.

RUSTOMJI, P. 2009. A statistical analysis of flood hydrology and bankfull discharge for the Daly River catchment, Northern Territory, Australia. *Water for a Healthy Country National Research Flagship.* Canberra, Australia: CSIRO.

SINGH, V. P. & STRUPCZEWSKI, W. G. 2002. On the status of flood frequency analysis. *Hydrological Processes,* 16**,** 3737-3740.

SVENSSON, C., KUNDZEWICZ, W. Z. & MAURER, T. 2005. Trend detection in river flow series: 2. Flood and low-flow index series. *Hydrological Sciences Journal,* 50.

TAKEUCHI, K. 1984. Annual maximum series and partial-duration series — Evaluation of Langbein's formula and Chow's discussion. *Journal of Hydrology,* 68**,** 275-284.

VIGLIONE, A. 2009. Non-supervised Regional Frequency Analysis. Version 0.6-9 ed.

VOGEL, R. M., MCMAHON, T. A. & CHIEW, F. H. S. 1993. Floodflow frequency model selection in Australia. *Journal of Hydrology,* 146**,** 421-449.

WOODYER, K. D. 1966. Interpretation of Recurrence Intervals. *Australian Journal of Science,* 29**,** 145.

WOODYER, K. D. 1968. Bankfull frequency in rivers. *Journal of Hydrology,* 6**,** 114-142.

Chapter 3 The estimation of bankfull stage from plotted channel geometries

Abstract: Bankfull stage is a fundamental concept in river hydrology and geomorphology, however no satisfactory objective, consistent and repeatable method for determining bankfull stage from river channel profiles exists. This study compared two quantitative methods for determining bankfull stage from plotted channel cross-sections - the minimum width-to-depth ratio and the first maximum of the bench-index - and evaluated them against qualitative estimates of bankfull stage on 89 cross-sectional surveys undertaken along nine river reaches in north-eastern Tasmania. The minimum width-to-depth ratio was found to provide lower values than the bench-index, with an overall mean ratio between the two methods of 0.84. Qualitative estimates of bankfull stage generally fell between those provided by the two models, with the minimum width-to-depth ratio performing better when assessed against qualitative estimates. These findings show that while neither method offers a suitable stand-alone means for estimating bankfull stage, in combination they may provide a means to approximate the range of bankfull stage and serve as a useful adjunct to other methods. The high variability in bankfull stage found along a reach in the study suggests that where possible bankfull stage should be considered at the reach rather than cross-sectional scale.

3.1. Introduction

Bankfull is a critical concept in fluvial geomorphology (Knighton, 1998, Wohl, 2010) and also has significant applications in relation to hydrological and ecological processes (Navratil et al., 2010) as well as being an important design parameter in stream rehabilitation, habitat creation and related projects (He and Wilkerson, 2011). The elevation or depth at which bankfull occurs, known as the bankfull stage, is a widely used measure of bankfull, and it is commonly applied in three ways. Firstly, bankfull stage marks the point above which the river channel becomes connected with the floodplain. When discharge exceeds bankfull stage, biotic and abiotic elements including aquatic organisms, vegetation, sediment and nutrients are transferred and redistributed (Bouwman et al., 2013). Consequently the frequency and extent with which flow exceeds the channel has important ecological and geomorphological consequences, and is also of importance to the design of infrastructure, flood mapping and insurance (Richards, 1982, Dutta et al., 2003).

Secondly, the discharge which occurs at bankfull stage has been linked to channel formation. In a highly influential work, Wolman and Miller (1960) suggested that while discharge events of varying magnitude, frequency and temporal structure influence channel form, the channel morphology of alluvial rivers appears to be associated with flows at or near the bankfull stage. As discussed in Section 1.3, the correlation between channel shape and bankfull discharge has since been widely debated, particularly in Australia (e.g. Pickup and Warner, 1976), as Australian rivers have been found to have important differences from those in most other parts of the world, with more variable flow regimes (Finlayson and McMahon, 1988), and a sediment load dominated by fine suspended particles and with a reduced coarse sediment load because of the stability of the continent and the almost complete absence of Quaternary glaciations (Tooth and Nanson, 1995). However ideas of a channel forming discharge to which the channel geometry becomes adjusted continue to be central to fluvial geomorphology studies (Doyle et al., 2007).

The third common bankfull stage application is as the one reference level which can reasonably be defined amongst the complexity of river morphology (Knighton, 1998). In this role bankfull is widely used to compare spatial and temporal variations in stream metrics. Bankfull parameters such as bankfull stage, bankfull width and bankfull discharge are extensively used in hydrology and fluvial geomorphology studies, as well as in river classification (e.g. Rosgen, 1994) and river health assessment systems (e.g. NRM South, 2009).

3.1.1. Definitions of bankfull stage

Different bankfull stage applications have led to a number of definitions (for summaries see Williams, 1978, Radecki-Pawlik, 2002), many of which are conflicting. In some studies, bankfull stage has been defined in a theoretical sense, attained when water reaches a point not necessarily associated with the physical top of the banks (Stream Systems Technology Centre, 1993). These theoretical definitions commonly equate bankfull stage with an abstract discharge such as “bankfull stage corresponds to the discharge at which channel maintenance is the most effective” (Dunne and Leopold, 1978) or relate it to the recurrence frequency of a flood event, such as “the stage occupied by the 1.58 year flood on the annual series” (Dury et al., 1963, quoted in Pickup, 1976).

In contrast to the theoretical definitions, a range of physical definitions of bankfull stage have been made, based on recognition of sedimentary surfaces, observation or measurement of boundary features or geometrical properties (Williams, 1978). Among many of these physical definitions, differences exist as to the particular stage at which bankfull occurs. Definitions range from the stage at which discharge just fills the stream channel without overflowing onto the floodplain (Williams, 1978, Gordon et al., 2004, Gomez et al., 2007), the stage at which discharge just overflows the banks of the channel onto the floodplain (Page, 1988), or the elevation of the active floodplain (Wolman and Leopold, 1957, Wolman and Miller, 1960) (Figure 3.1).

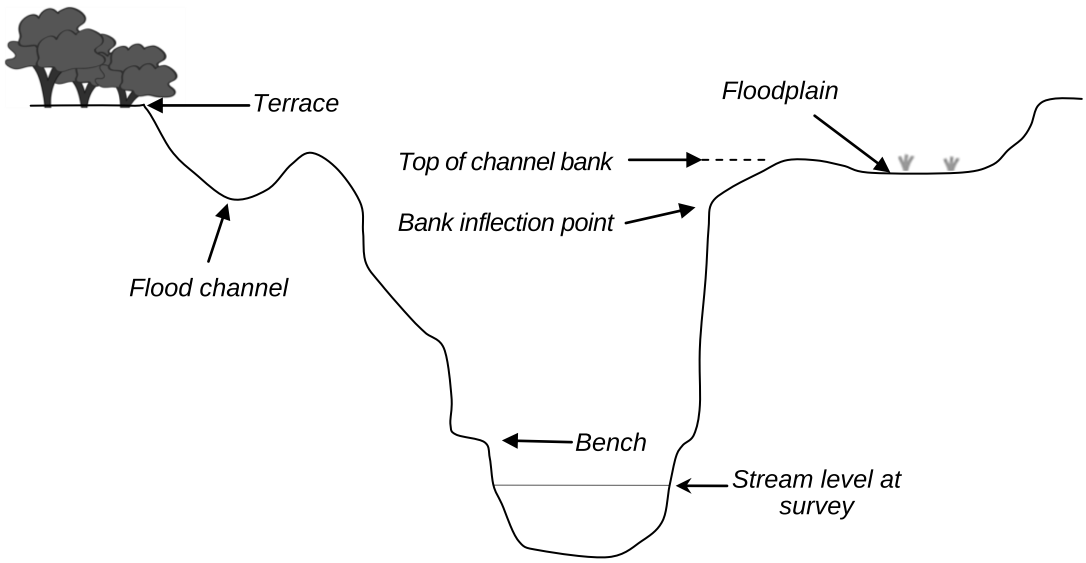


Figure3.1. Major bankfull morphological features of an idealised river channel cross-section.

Although the differences in elevation between these various definitions may be small, at the point of bankfull minor increases in depth are often accompanied by large increases in width, and a slight difference in interpreting bankfull stage elevation can lead to significantly different values in other bankfull parameters (Leopold et al., 1964, Gordon et al., 2004, Wilkerson, 2008). In light of these difficulties, it has been suggested that bankfull stage is rather a transition zone extending from the point of bank inflection to the top of bank elevation (Navratil et al., 2006) and should be presented as a range of values (Johnson and Heil, 1996, Radecki-Pawlik, 2002).

3.1.2. Determination of bankfull stage using qualitative methods

The most frequently used method to determine bankfull stage is based on qualitative field observations of evidence such as scour lines, vegetation limits, changes between bed and banks material, abrupt changes in slope or most commonly, the active floodplain. However floodplains are not always present, they may be difficult to identify, and they may not relate to the current river form. For example, in eastern Australia numerous rivers have been found to have a channel geometry and planform fundamentally altered from natural condition, with many apparent floodplains flooded relatively infrequently and not in adjustment with the present stream regime (IEA 1987). Incised rivers in both Queensland (Dury et al., 1963) and New South Wales (Woodyer, 1968) have been found to have an active floodplain that is actually a bench contained within the channel, while the apparent floodplain is in fact a terrace. Additionally, within a river a number of benches may be present (Woodyer, 1968), and bankfull stage may not always be associated with the same bench along a stream reach (Radecki-Pawlik, 2002). Bankfull stage can be particularly difficult to identify in unstable streams (Simon et al., 2004), or where the river is adjusting to a new equilibrium.

Despite numerous detailed definitions of bankfull stage being developed in recognition of the difficulty in identifying the active floodplain (Gippel, 1985, Page, 1988, De Rose et al., 2008, Harman et al., 2008), identifying bankfull stage in the field continues to rely on subjective judgment, and may result in inconsistent estimates if observers do not have sufficient training or experience (Rosgen, 2009).

3.1.3. Determination of bankfull stage using quantitative methods

Attempts to develop more objective and repeatable methods for determining bankfull stage arose as fluvial geomorphology moved from qualitative to more quantitative techniques. Quantitative methods offer considerable benefits over qualitative methods: they do not rely on the presence of an active floodplain or other often subjective field evidence, and they enable bankfull stage to be determined without field observations or expert assessment. This allows the use of remotely sensed data or other data collected for purposes other than identifying bankfull stage. In addition, quantitative techniques generally use fewer resources than field based methods and are more objective (Williams, 1978). However some studies have found that quantitative methods inadequately define bankfull stage (Riley, 1972, Gregory, 1976), they do not provide significantly greater accuracy then visual field inspection (Williams, 1978), or they are less relevant than morphological definitions (Navratil et al., 2006). The two most common quantitative methods are the minimum width-to-depth ratio and the first maximum of the bench-index.

3.1.3.1. Width-to-depth ratio

The ratio of the channel width (*W*) to mean channel depth (*D*) (Figure 3.2) has been extensively used as a measure of channel shape (Figure 1) and is determined according to Equation 3.1:

$$R_{WD} = \frac{W}{D} \tag{3.1}$$

The use of the width-to-depth ratio to determine bankfull stage is often attributed to Wolman (1955), who defined 'bankfull' as that stage at a given cross-section at which, in a plot of the width-to-depth ratio against stage, the curve breaks sharply and the width becomes exceedingly large (Figure 3.2). However rather than associate this stage with the physical top of the channel banks, Wolman suggested that above this point the channel begins to flare out and depart from the more rectangular shape prevailing below this stage (Wolman, 1955). This point may correspond with the Bank Inflection point (Figure 3.1), which corresponds to the main change in bank slope, i.e. the end of the abrupt part of the bank (Navratil et al., 2006).

A number of subsequent works have departed from Wolman's methods and associated a 'top-of-bank' bankfull with the stage at which the width-to-depth ratio is at a minimum (Harvey, 1969, Riley, 1972, Pickup and Warner, 1976, Pickup, 1976, Johnson and Heil, 1996, Copeland et al., 2000, Gordon et al., 2004, Gomez et al., 2007). Despite a number of studies suggesting that the minimum width-to-depth ratio generally underestimates bankfull stage (Riley, 1972, Williams, 1978, Navratil et al., 2004, Navratil et al., 2006), this method continues to be used for determining bankfull stage from plotted channel geometries.

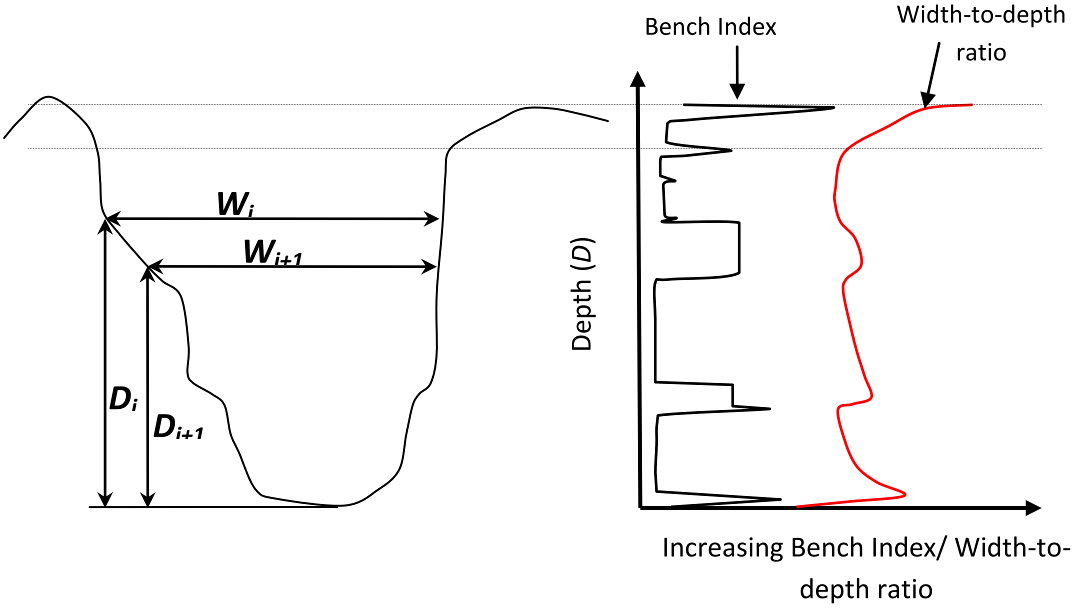


Figure 3.2. Determination of Bench Index and width to depth ratio using an idealised river channel cross-section (*W* = width, *D* = depth, *i* = the channel at a particular stage and *i + 1* = the channel at a lower increment of stage).

3.1.3.2. Bench Index

In an attempt to develop a method for identifying bankfull stage that was less dependent on subjective judgement and more 'amenable to computer operations', Riley (1972) defined a bench-index (*BI*) as:

$$BI = \frac{[W_i - W_{i+1}]}{[D_i - D_{i+1}]} \tag{3.2}$$

where i = 1, 2, 3,... x, and x is the number of unique width and depth measurements available ranked in ascending value (i.e. the greater the value of i the closer to the channel bed) (Figure 3.2). The bench-index measures the relative slope of a segment of channel profile, with high values indicating relatively horizontal channel segments and low values defining relatively vertical segments (Riley, 1972) (Figure 3.2). Based on the results from 20 stream sites in north-western New South Wales with a wide range of cross-sectional areas and profile shapes, Riley found that when plotted against depth, the bench-index showed a marked peaked value near the bankfull stage and consequently suggested that bankfull stage was equivalent to the first maximum of the bench-index when measured in descending elevations (decreasing depth). However a number of subsequent studies have found that the first maximum of the *BI* significantly overestimated bankfull stage on some reaches (Williams, 1978, Radecki-Pawlik, 2002, Navratil et al., 2004, Navratil et al., 2006).

3.1.4. Aims

This study aimed to evaluate two quantitative methods for determining bankfull stage from plotted cross-sections on north-eastern Tasmanian Rivers. The minimum width-to-depth ratio and the first maximum of the bench-index were compared and evaluated against qualitative estimates of bankfull stage using data from 89 cross-sectional surveys undertaken at nine river reaches in different catchments.

3.2. Materials and Methods

3.2.1. Environmental context

The fluvial geomorphology of the rivers of Tasmania, a continental island located from around 41 to 43 degrees latitude has significant differences from those of mainland Australia to the north. The highly variable Tasmanian landscape includes areas which have experienced relatively recent tectonic activity and glaciation (Sharples, 1996) which, combined with the large variations in hydrology and lithology, has resulted in a wide variety of channel and floodplain forms across Tasmanian catchments (Cohen and Houshold, 2005).

North-eastern Tasmania is a region geologically and to some extent geomorphologically distinct from the rest of Tasmania (Sharples, 1996). The marine turbidite rocks (the Mathinna Group) on which the region is founded were deposited in a location at some distance from the rest of Tasmania and then tectonically transported to their present position. Much of the region was subsequently uplifted, with thin sequences of Permian sedimentary rock then being deposited in the present highland areas before being intruded by extensive sheets of dolerite magma during the mid-Jurassic. Fluvial processes have been the major forces acting on the landscape since the early Tertiary, and it has been suggested that many watercourses in the region possess underfit streams (Sharples, 1996). The temperate marine climate is interrupted by occasional intense and sustained rainfall events which can trigger major flooding in the north-east (Fox-Hughes, 2009). Despite some anthropogenic impacts including alluvial mining, forestry, agriculture and grazing, and in contrast to south-eastern

Australia, the majority of streams in north-eastern Tasmania remain largely unmodified and unregulated, although significant water resource developments are planned for the region.

The nine study reaches were located on eight rivers across six catchments in north-eastern Tasmania (Figure 3.3 and Table 3.1), ranging in size from the Third River at Paling Track, a first order stream with an upstream catchment area of just 4.4 km^2, to the South Esk River at Ormley, a sixth order stream with a catchment area of over 1360 km^2. Sites were either in a unconfined or partially confined valley setting. All sites were set in unconsolidated sediments and were judged to have a river channel largely free to adjust to discharge. This can be evidenced in the meandering planform of rivers (Figure 3.3).

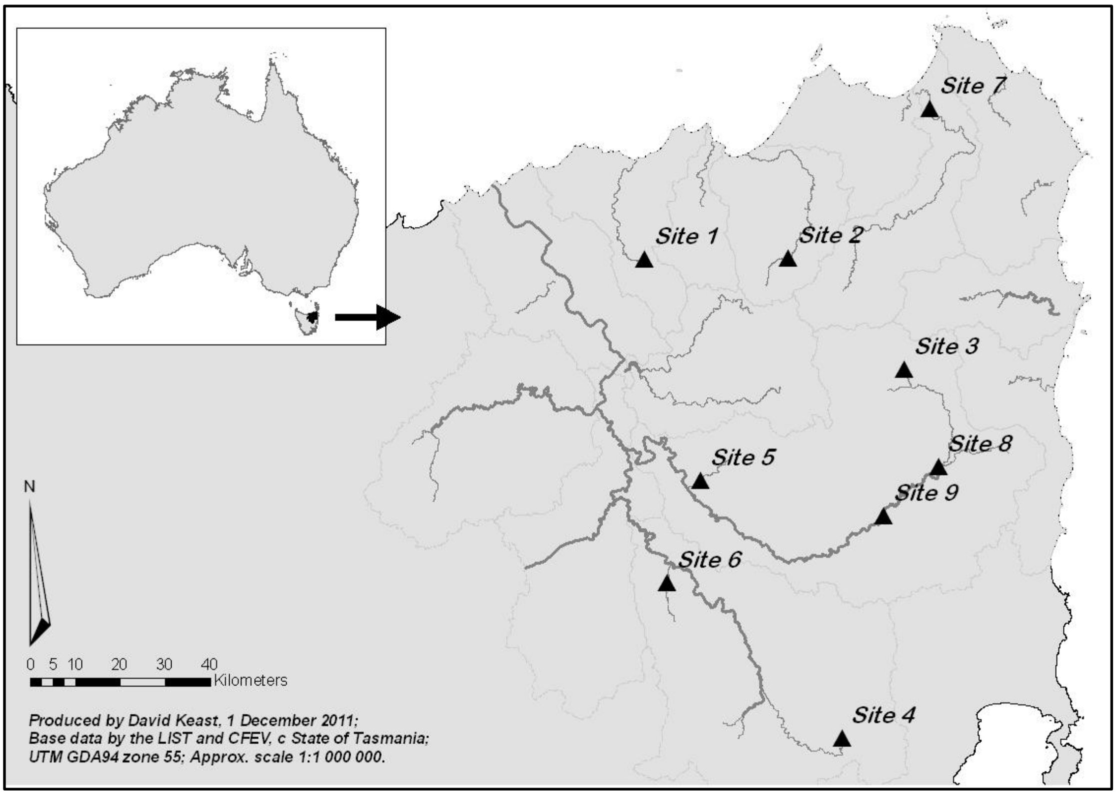


Figure 3.3. North-eastern Tasmania showing the location of major rivers and the study sites listed in Table 3.1.

3.2.2. Data

Channel cross-sectional survey data for eight of the nine river reaches listed in Table 3.1 was obtained from the Tasmanian Department of Primary Industries, Parks, Water and Environment (DPIPWE). These survey data were collected for a variety of purposes including the establishment of environmental flow levels.

Table 3.1. Details of the sites used in this study including elevation, upstream catchment area, the number of cross-sectional surveys undertaken and the river type based on valley setting. Images from Google Earth, 2015.

Site	Name	Number of cross sections	Max elevation (m ASL)	Upstream catchment area (km^2)	River type	Image
1	Third River at the Paling Track	5	187	4.42	Partially Confined	
2	Great Forester River at Prosperity Road	11	126	64.62	Partially Confined	
3	Dans Rivulet upstream of Mathinna Plains Road	6	315	72.60	Unconfined	
4	Macquarie River at Honeysuckle Road	10	296	169.31	Partially Confined	
5	Nile River at Nile	12	181	253.44	Unconfined	
6	Isis River at Isis	9	159	311.35	Unconfined	
7	Ringarooma River at wetlands	12	6	878.08	Unconfined	

8	South Esk River at Malahide	12	225	1023.34	Partially Confined	
9	South Esk River at Ormley	12	202	1360.45	Partially Confined	

Surveys of cross-sections were carried out between August 2006 and October 2007, with between 5 and 12 cross-sections spaced 15 to 40 m apart undertaken at each reach. The number of cross-sections and their separation was based on subjective judgement, with the complexity of the physical form of the river channel taken into account. The general approach adopted in this study was that to minimize error in bankfull stage parameter estimation more cross-sections should be undertaken on more variable channels (Harman et al., 2008). Rather than using prescriptive measures to identify site location and the number and location of cross-sectional surveys, place-based understanding (Brierley et al., 2013) was adopted, where practioner knowledge and place-based understandings are used to detect where local differences matter, thereby addressing concerns for the transferability of insights between locations and the representativeness of sample or reference sites (Brierley et al., 2013). The Third River at Paling Track (Table 3.1) for example, was a relatively small upper catchment stream with a simple channel that displayed little variability in channel morphology along the reach. Based on the relatively homogenous channel morphology, 5 cross sectional surveys were considered sufficient to capture reach morphological variability.

Additional cross-sectional survey data collected from some sites was excluded from the study due to the presence of bedrock outcrops or an anabranching channel making bankfull channel impossible to identify. Cross-sections targeted a range of channel forms (pool, riffle, run) where they existed, and included a range of channel types from simple channels to complex channels with features including in-channel benches, overbank terraces and floodshutes. Cross-sectional surveys extended from above obvious bankfull flow levels on one bank to a similar elevation on the opposite river bank but focused on the proportion of the channel at and below the bankfull flow thresholds; therefore, at most sites, surveying of the extended floodplain (if present) was not undertaken (DPIPWE, 2010). All sites were surveyed at low-flow conditions. To ensure a wide range of channel sizes were included in the study, an additional reach (Site 1) was surveyed in December 2010 following the procedures outlined above.

The software package Win XSPRO (Grant et al., 1992) was used to plot each cross-section and to model cross-sectional channel parameters at 0.01 m increments in stage from the deepest point of the channel to well above the maximum elevation of the lowest channel bank of the survey. Plots were modified in some instances by removing features such as floodchutes to ensure that only a single channel was considered at each increment. All statistical analyses were undertaken using the statistical software package R (version 2.12.0).

3.2.3. Minimum width-to-depth ratio (*WD*)

The ratio of channel width-to-depth was calculated at 0.01 m stage increments for each cross-section by dividing the channel width (W) by the mean depth (D) (Equation 3.1). Following common practice, this study used mean depth (mean depth = cross-sectional area (A) / width (W)). Bankfull using the *WD* method was defined as the stage at which the minimum of the width-to-depth ratio occurred. A lower limit of 50% of the maximum elevation of the lowest channel bank was set to eliminate low width-to-depth values which occurred at very low stages due to irregularities on the floor of the channel.

3.2.4. First maximum of the bench-index (*BI*)

Bankfull stage using the bench-index was determined largely according to the methods of Riley (1972). However as channel parameters were modeled at equal increments (0.01 m), $D_{\mathrm{i}} - D_{\mathrm{i}+1}$ remains constant and may be removed from Equation 3.2 to produce:

$$\text{Bench Index } (BI) = W_i - W_{i+1} \tag{3.3}$$

where i = 1,2, 3,...x, and x is the number of unique width and depth measurements available ranked in ascending value (i.e. the greater the value of i the closer to the channel bed). Following Riley (1972), the stage that corresponded with the first maximum of the bench-index from upper (the maximum elevation of the lowest channel bank) to lower elevation was bankfull stage. Neither Riley nor subsequent studies explained the method used to identify the maximum, and in this study maxima were identified using a simple algorithm:

If $BI_{i+1} > BI_i$, let $BI_i = BI_{i+1}$;
If $BI_{i+1} = BI_i$, go to BI_{i+2} continue to repeat through to i+5.
If $BI_{i+5} = BI_i$, then BI_i is equivalent to bankfull stage.
If $BI_{i+1} < BI_i$, then BI_i is equivalent to bankfull stage.

Where consecutive increments had equivalent values, the upper increment was determined to be equivalent to bankfull stage, as this was thought to be more in line with the methods of Riley (1972).

3.2.5. Qualitative estimates of bankfull stage

This study adopted the physical definition of bankfull used by Riley (1972) as the stage above which flow would exceed the active channel banks. This was chosen as it provided the most objective and consistent definition for quantitative comparisons. Definitions based on floodplain elevation were rejected as being often subjective and because floodplains were not always present. Ideally bankfull stage models should be compared with the 'true' bankfull stage, however the chances of being present to measure bankfull parameters just at bankfull are extremely small (cf. Williams, 1978), and consequently bankfull stage values can only ever be an estimate. In this study bankfull stage was estimated at each cross-section by interpretation of plotted channel profiles, with particular attention paid to channel morphological features which could be observed across a number of cross-sections along a reach. Field observations and notes were used to assist this process where available. A 3D multiple-cross-section plot was also created in some instances to ensure that the estimated bankfull elevation at each cross-section was consistent along a reach.

3.2.6. Model evaluation

Previous studies evaluating quantitative bankfull stage models have used a range of techniques including largely qualitative measures (Williams, 1978) and flow models to compare derived bankfull discharge values (e.g. Navratil et al., 2006). This study uses a mix of quantitative and qualitative methods to assess the performance of the two quantitative bankfull stage models. It first compares the ratio between bankfull stage estimates derived using the minimum width-to-depth ratio (*WD*) and those determined using the first maxima of the bench-index (*BI*) and conducts paired t-tests to consider the differences between the two methods in comparison to the overall and within-a-reach variability.

This study also evaluated bankfull stage models against qualitative estimates of bankfull stage using guidelines which were developed to evaluate watershed models and their input parameters (Moriasi et al., 2007). These guidelines suggest a combination of graphical techniques and dimensionless and error index statistics be used in model evaluation, and more specifically recommend the use of three quantitative statistics, Nash-Sutcliffe efficiency (*NSE*), percent bias (*PBIAS*), and ratio of the root mean square error to the standard deviation of measured data (*RSR*). While not developed for the evaluation of bankfull stage models, each of the recommended statistics from the guidelines can be used to describe the predictive accuracy of models other than discharge, and together they provide a comprehensive and relevant assessment method (Moriasi et al., 2007).

The Nash-Sutcliffe efficiency (*NSE*) is a dimensionless statistic that determines the relative magnitude of the residual variance in comparison to the measured data variance (Moriasi et al., 2007). The flexibility of *NSE* as a goodness of fit measure has resulted in it being widely used for a variety of model types (McCuen et al., 2006). *NSE* is calculated using Equation 3.4:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{mean})^2}\right] \tag{3.4}$$

where Y_i^{obs} is the *i*th observation for the constituent being evaluated, Y_i^{sim} is the *i*th simulated value for the constituent being evaluated, Y^{mean} is the mean of observed data for the constituent being evaluated, and n is the total number of observations (Moriasi et al., 2007). *NSE* values range between $-\infty$ and 1.0, with $NSE = 1$ being the optimal value and values between 0.0 and 1.0 generally viewed as acceptable levels of performance. Values < 0.0 indicate that the residual variance is larger than the data variance, which indicates unacceptable performance (Moriasi et al., 2007). However as the *NSE* can be sensitive to a number of factors including sample size, outliers, and magnitude bias, incorrect interpretation of the results can be misleading and it should be used in conjunction with other analyses (McCuen et al., 2006). To assist in identifying true outliers and assessing the relevance of calculated *NSE* values, Z-scores, which are commonly used to provide a standardised measure of the distance of an observation from the mean, were determined for each qualitative estimate of bankfull stage (*BF*) using sample mean and standard deviation.

Percent bias (*PBIAS*) measures the average tendency of the simulated data to be larger or smaller than their observed counterpart, and has the ability to clearly indicate poor model performance (Gupta et al., 1999). *PBIAS* is determined using Equation 3.5:

$$PBIAS = \left[\frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim}) * (100)}{\sum_{i=1}^{n} (Y_i^{obs})} \right] \tag{3.5}$$

where *PBIAS* is the deviation of data being evaluated, expressed as a percentage. The optimal value of *PBIAS* is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta et al., 1999).

The root mean square error (*RMSE*) to the standard deviation of the measured data (RSR) is calculated by Equation 3.6:

$$RSR = \frac{RMSE}{\mathrm{STDEV}_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right)^2} \right]}{\left[\sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean}\right)^2} \right]} \tag{3.6}$$

RMSE is a commonly used error index statistic, but while lower values of *RMSE* are generally regarded as better, there is little guidance to what is a good level of *RMSE*. *RSR* incorporates the benefits of error index statistics and includes a scaling/normalization factor that is based on the standard deviation of the observations. *RSR* varies from the optimal value of 0, which indicates zero *RMSE* or residual variation and therefore perfect model simulation, to a large positive value. The lower the *RSR*, the lower the *RMSE*, and the better the model simulation performance (Moriasi et al., 2007).

Moriasi et al. (2007) suggested that watershed streamflow model simulation can generally be judged as satisfactory if *NSE* > 0.50 and *RSR* < 0.70, and these values have been adopted in this study for bankfull stage model evaluation. Performance ratings for *PBIAS* depend on the application, and in this study have been set at +/- 15%.

The results are also presented graphically as a plot of mean reach bankfull stage values with associated 95% confidence intervals (*CI*). Non-parametric confidence intervals were constructed using a bootstrap resampling method in R (Canty and Ripley, 2014) with 2000 iterations (DiCiccio and Efron, 1996). Bootstrapping allows robust non-parametric estimates of a parameter to be calculated from a sample by repeatedly taking random samples, with replacement, from the original sample and re-calculating the parameter (Canty and Ripley, 2014).

3.3. Results

The mean ratios between bankfull stage values determined using the minimum width-to-depth ratio (*WD*) and those determined using the first maxima of the bench-index (*BI*) for each reach as well as for the combined 89 individual cross-sections, along with the results of the paired t-tests are shown in Table 3.2. The results of bankfull stage model evaluation against qualitative estimates using *NSE*, *RSR* and *PBIAS* are shown in Table 3.3 along with co-efficient of variation (*CV*) values, and graphs of reach-averaged bankfull stage parameters and 95% confidence intervals calculated from bootstrapped samples for estimated and model derived bankfull stage are shown in Figure 3.4.

The mean ratio between *WD* and *BI* derived estimates across all 89 individual cross-sections was 0.84, with a range of 0.56 to 0.96 for mean reach ratios between *WD* and *BI* derived estimates. There was a significant overall difference between *WD* and *BI* derived estimates of bankfull stage (t = -10.35, df = 88, p = 0.0000) for the combined eighty-nine cross-sections, and for seven of the nine reaches (No significant difference for Site 3 and Site 7) (Table 3.2).

Table 3.2. Mean ratios between bankfull stage estimates using the minimum width-to-depth ratio (*WD*) and first maxima of the bench-index (*BI*) models along with paired t-test results, for each reach as well as for the combined eighty-nine individual cross-sections (*df*=degrees of freedom).

Site	1	2	3	4	5	6	7	8	9	Combined
WD/BI	0.56	0.90	0.88	0.76	0.80	0.64	0.96	0.90	0.93	0.84
df	4	10	5	9	11	8	11	11	11	88
t-value	-5.86	-2.80	-2.57	-6.75	-5.64	-4.68	-1.62	-5.43	-3.27	-10.35
p-value	0.0042	0.0188	0.0501	0.0001	0.0002	0.0016	0.1344	0.0002	0.0075	< 2.2e-16

Table 3.3. Results of minimum width-to-depth ratio (*WD*) and first maxima of the bench-index (*BI*) bankfull stage models evaluated against qualitative estimates of bankfull stage (*BF*) using Nash-Sutcliffe efficiency (*NSE*), root mean square error to the standard deviation of the measured data (*RSR*) and percent bias (*PBIAS*) for study reaches on north-eastern Tasmanian Rivers. Bold results indicate unsatisfactory performance based on *NSE* < 0.50, *RSR* > 0.70 and *PBIAS* > 15%. Also included are the coefficients of variation of bankfull stage (*CV*) for each reach and the number of samples (*n*) (CV_{BF} = coefficient of variation of qualitative estimates of bankfull stage for each reach).

Site	***n***	CV_{BF}	***WD***				***BI***			
			NSE	***RSR***	***PBIAS***	***CV***	***NSE***	***RSR***	***PBIAS***	***CV***
1	5	0.44	0.88	0.34	9.73	0.41	**-1.48**	**1.57**	**-56.84**	0.16
2	11	0.30	0.96	0.21	2.90	0.28	0.60	0.63	-10.54	0.30
3	6	0.29	0.82	0.42	-4.52	0.36	**0.21**	**0.89**	**-18.73**	0.30
4	10	0.15	**-0.62**	**1.27**	7.18	0.29	**-2.52**	**1.88**	**-21.41**	0.24
5	12	0.18	0.64	0.61	5.74	0.18	**-1.21**	**1.49**	**-18.05**	0.17
6	9	0.26	**-1.53**	**1.59**	**29.50**	0.19	**0.34**	**0.81**	**-15.51**	0.22
7	12	0.17	0.96	0.20	1.22	0.18	0.76	0.49	-3.10	0.15
8	12	0.06	**-1.97**	**1.72**	7.63	0.09	**0.34**	**0.81**	-2.45	0.05
9	12	0.10	**0.06**	**0.97**	5.75	0.15	0.97	0.16	-0.58	0.10

Bankfull stage values determined using the *WD* method were generally less than qualitative estimates of bankfull stage (*BF*), with an overall *PBIAS* value of 6.59% across all 89 cross-sections and positive *PBIAS* values (underestimation) on eight of the nine reaches ranging from 1.22 to 29.50% (Table 3.3). *PBIAS* values fell below 15% on eight of the nine reaches. *NSE* values ranged from -1.97 to 0.96, with four reaches having *NSE* values less than or equal to 0.50. *RSR* values ranged from 0.20 to 1.72, with four reaches having values greater than or equal to 0.70. Four of the nine reaches fell outside satisfactory model performance based on the evaluation suggested by Moriasi (2007). The *WD* derived mean reach bankfull stage fell within the 95% Confidence Intervals for *BF* on all reaches apart from Sites 6 and 8, and the 95% Confidence Intervals for *WD* derived mean reach bankfull stage overlapped the 95% Confidence Intervals for *BF* on all reaches apart from Site 6 (Figure 3.4).

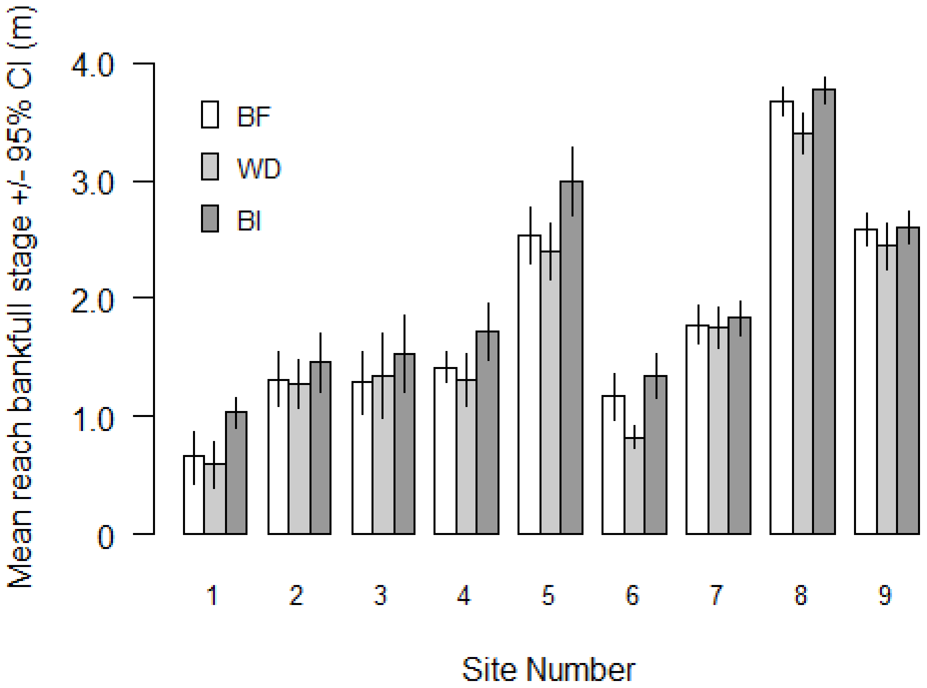


Figure 3.4. Mean reach bankfull stage and 95% confidence intervals for study reaches on north-eastern Tasmanian Rivers (*BF* = qualitative estimate of bankfull stage, *WD* = minimum width-to-depth ratio, *BI* = first maxima of the bench-index).

Bankfull stage values determined using the *BI* method were generally greater than qualitative estimates of bankfull stage (*BF*), with an overall *PBIAS* value of -9.55% across all 89 cross-sections, and negative *PBIAS* values (overestimation) on all nine reaches ranging from -0.58 to -56.84% (Table 3.3). *PBIAS* values were less than 15% from *BF* values on four of the nine reaches. *NSE* values ranged from -2.52 to 0.97, with six reaches having *NSE* values less than or equal to 0.50. *RSR* values ranged from 0.16 to 1.88, with six reaches having values greater than or equal to 0.70. Six of the nine reaches fell outside satisfactory model performance suggested by Moriasi (2007). The *BI* derived mean reach bankfull stage fell within the 95% *CI* for *BF* on all reaches apart from Site 1 (Figure 3.4). A number of reaches had individual *BF* values which may be considered outliers, with five of the eighty-nine cross-sections having z-scores in excess of +/- 1.75. However there was not a strong correlation between reaches with *BF* outliers and those which had low *NSE* values for either *BI* or *WD*. The range of values between the upper and lower 95% CI of BF was fully contained between the upper 95% CI of BI and the lower 95% CI of WD for each site.

The co-efficient of variation (*CV*) for qualitative estimates of bankfull stage (*BF*) along a reach ranged from 0.06 to 0.44 (Table 3.3), while the *CV* for the minimum width-to-depth ratio (*WD*) ranged from 0.09 to 0.41, and the *CV* for first maxima of the bench-index estimates of bankfull stage (*BI*) along a reach ranged from 0.05 to 0.30 (Table 3.3). There was similarity in the patterns of CV variability between sites for *WD*, *BI* and *BF*.

Variation between best estimate (*BF*), width-to-depth ratio (*WD*) and Bench Index (*BI*) bankfull stage for individual cross-sections along three example reaches, the Third River at Paling Track (Site 1), the Nile River at Nile (Site 5) and Isis the River at Isis (Site 6), are shown in Figures 3.5, 3.7 and 3.9 respectively. Channel profiles for selected cross-sections from each of the three examples are shown in Figures 3.6, 3.8 and 3.10.

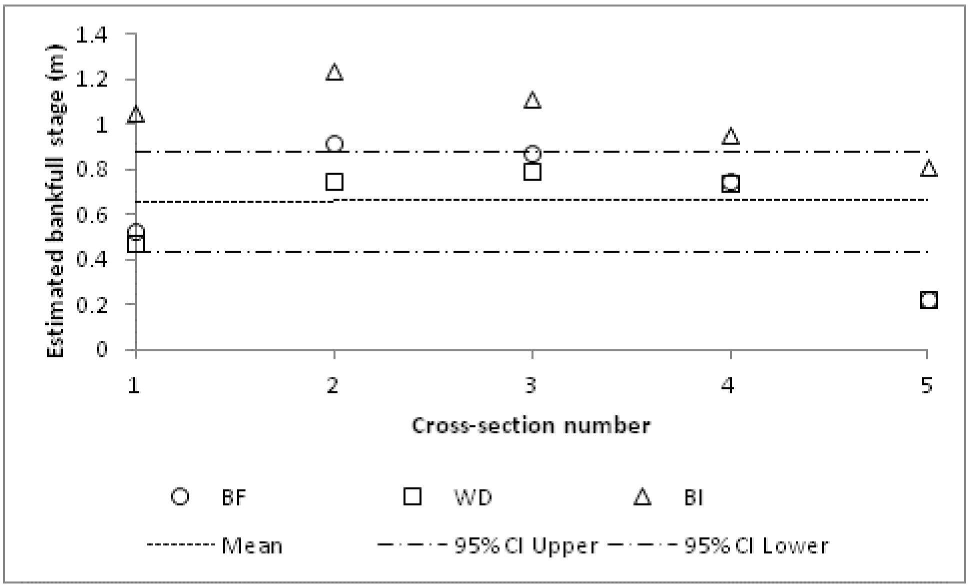


Figure 3.5. Variation between estimated bankfull stage using best estimate (*BF*), width-to-depth ratio (*WD*) and Bench Index (*BI*) for individual cross-sections along the reach at Site 1, The Third River at Paling Track. Mean reach best estimate of bankfull stage and associated 95% confidence intervals (CI) are also shown.

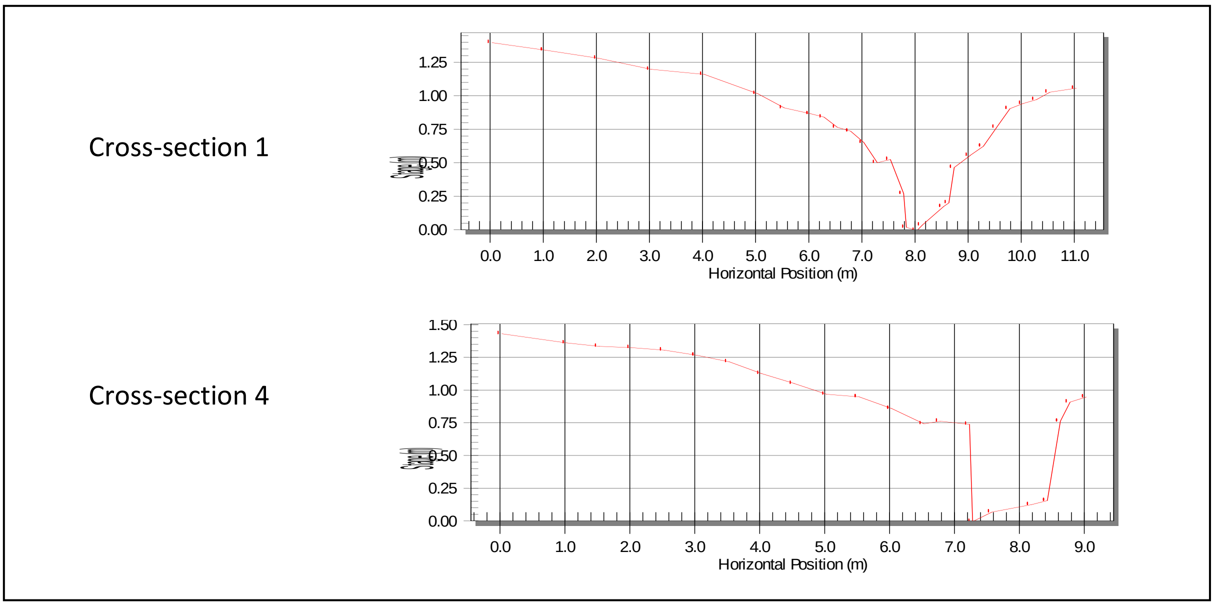


Figure 3.6. Channel profiles for two cross-sections from Site 1, The Third River at Paling Track.

Bankfull estimates at the Third River at Paling Track (Figure 3.5) varied both between methods and along the reach. There was also considerable variation in the way the three estimates differed between reaches. At cross-section 1, the *WD* estimate was close to the *BF* estimate, both of which were below *BF* mean reach bankfull stage, with the *BI* estimate well above these (Figure 3.5). The river at this cross-section had a sloping channel bank on one side and a relatively vertical bank on the other side, with rounded top-of-channel banks and an ill defined floodplain (Figure 3.6). Cross-section 4 of the Third River at Paling Track had quite closely clustered *BF*, *WD* and *BI* estimates (Figure 3.5), and the river at this cross section had more vertical banks breaking to a horizontal section of floodplain on one side (Figure 3.6).

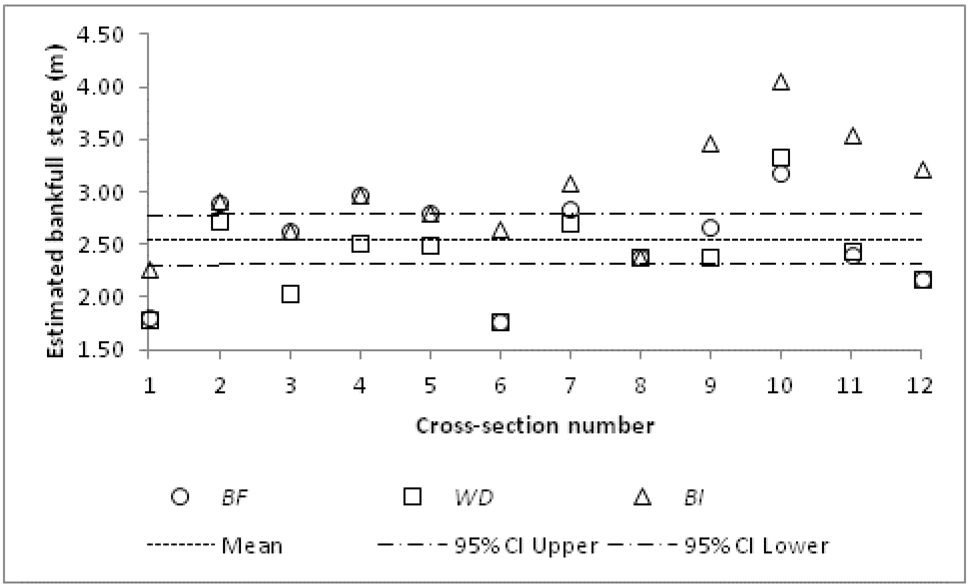


Figure 3.7. Variation between estimated bankfull stage using best estimate (*BF*), width-to-depth ratio (*WD*) and Bench Index (*BI*) for individual cross-sections along the reach at the Nile River at Nile. Mean best estimate bankfull stage and 95% confidence intervals (CI) are also shown.

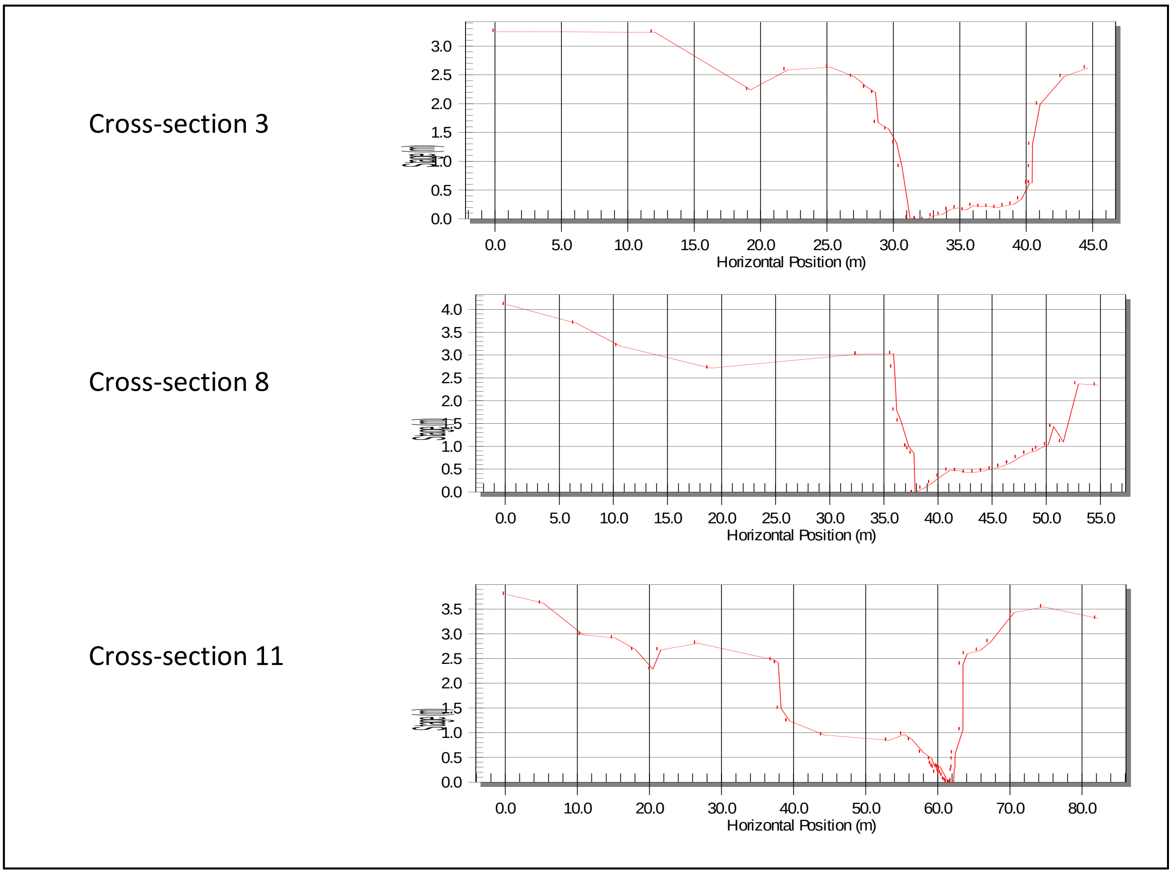


Figure 3.8. Channel profiles for three cross-sections at the Nile River at Nile.

The Nile River at Nile had relatively low variability in estimates of bankfull stage from cross-sections 1 to 8, but cross-sections 9 to 12 showed a strong rise and fall in bankfull stage (Figure 3.7). Cross-section 3 of the Nile River at Nile had a BI estimate equal to the BF estimate, with the WD estimate well below these and outside the 95% CI of mean reach BF. The river at this cross-section had slightly sloping channel banks and rounded top-of-channel banks (Figure 3.8). Cross-section 8 of the Nile River at Nile had both WD and BI estimates equal to BF estimates (Figure 3.7). The channel at this cross section had a clearly defined break between river channel and floodplain, with the floodplain angling downwards away from the top of channel (Figure 3.8). Cross-section 11 of the Nile River at Nile had WD estimates similar to BF estimates, with BI estimates well above both (Figure 3.7). The river channel at this location had a well defined break between channel and floodplain, but the floodplain angled upwards away from the channel (Figure 3.8).

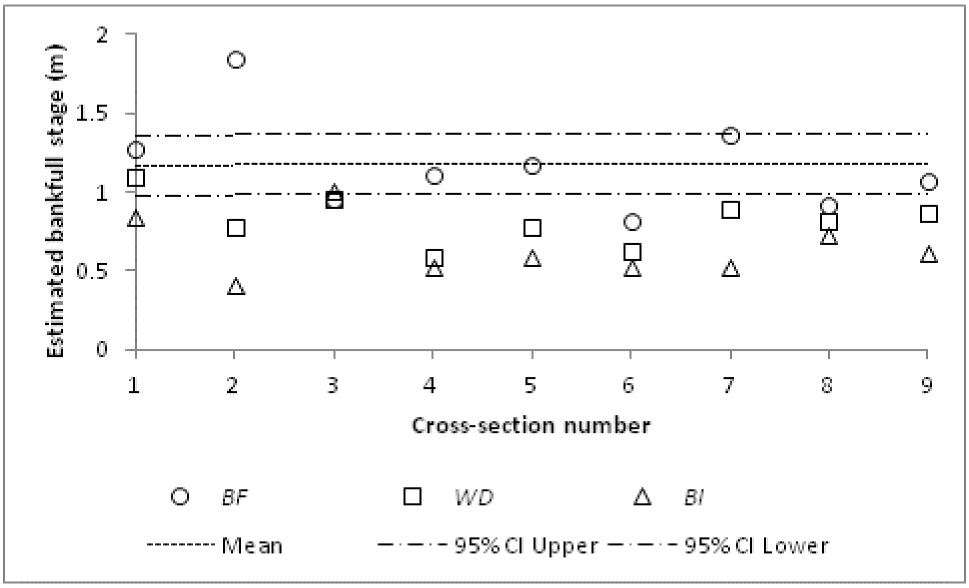


Figure 3.9. Variation between estimated bankfull stage using best estimate (*BF*), width-to-depth ratio (*WD*) and Bench Index (*BI*) for individual cross-sections along the reach at the Isis River at Isis. Mean best estimate bankfull stage and 95% confidence intervals (CI) are also shown.

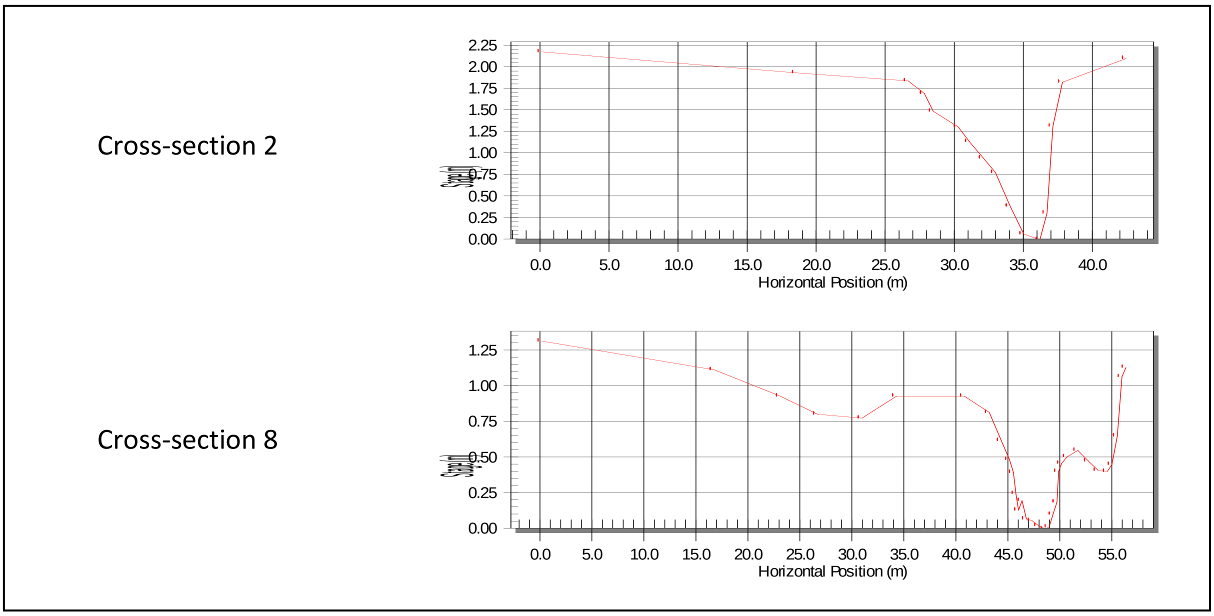


Figure 3.10. Channel profiles for two cross-sections at the Isis River at Isis.

There were no strong trends in bankfull estimates along the reach at the Isis River at Isis (Figure 3.9). Cross-section 2 from the Isis River at Isis had large differences between *BF*, *WD* and *BI* estimates. The channel at this location had sloping banks and a floodplain that sloped upwards away from the river channel (Figure 3.10). The river channel at cross-section 8 had a very different shape, with more vertical banks and a well defined horizontal section of floodplain between the main channel and a flood chute (Figure 3.10), and had closely clustered *BF*, *WD* and *BI* estimates (Figure 3.9).

3.4. Discussion

This study makes two contributions to the study of bankfull stage determination. Firstly, it compares two quantitative bankfull stage models and evaluates their performance against qualitative estimates of bankfull stage using data from north-eastern Tasmanian River reaches. Secondly, the results from this study are compared with those from other studies, and suggestions are made on how bankfull stage model performance may be improved and how bankfull stage may be defined.

3.4.1. Minimum width-to-depth ratio (*WD*)

The minimum width-to-depth ratio provided smaller mean reach estimates of bankfull stage than the bench-index on all study reaches, with significantly smaller estimates occurring on seven of the nine reaches (Table 3.2). Minimum width-to-depth ratio estimates were rated as unsatisfactory for four of the nine reaches when assessed against qualitative estimates, and were generally smaller than qualitative estimates of bankfull stage (Table 3.3). These results support the findings of previous studies which have found that the minimum width-to-depth ratio often underestimates bankfull stage (Riley, 1972, Williams, 1978, Navratil et al., 2004, Navratil et al., 2006).

Riley (1972) found the stage identified by the minimum width-to-depth ratio to be dependent on channel shape - close to the actual bankfull stage for channels with rectangular profiles, but nearer the channel bed for channels with shallow profiles and gently sloping banks. While this study did not quantitatively assess the *WD* method against channel shape, there were indications that the *WD* performed better on channel cross-sections with rectangular channel profiles. For example, the *WD* method identified a mean reach bankfull stage almost identical to that of qualitative estimates at Site 7 (The Ringarooma River at the Wetlands), which had a largely rectangular channel profile, but performed poorly against qualitative estimates at Site 6 (The Isis River at Isis) where the channel was quite complex, with in-channel benches on a number of cross-sections and a well developed flood chute occurring in the floodplain. Wolman suggested the minimum width-to-depth ratio identified the point above which point the channel begins to flare out and depart from the more rectangular shape prevailing below this stage (Wolman, 1955), and comparisons of width-to-depth plots with channel profiles from many of the cross-sections in this study support this view (Figure 3.11).

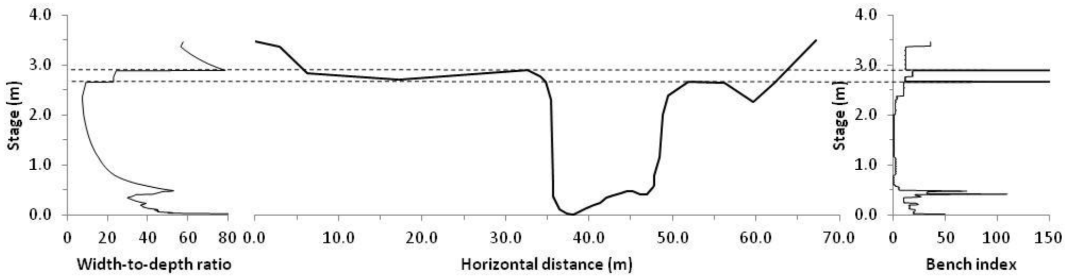


Figure 3.11. Plotted channel cross-sectional profile with associated plots of width-to-depth ratio and bench-index for Site 5, The Nile River at Nile. Note that for this cross-section the second maximum of the *BI* is equivalent to the qualitative estimate of bankfull stage (lower dotted line) and the minimum of the width-to-depth ratio is equivalent to the stage where the channel begins to flare out.

3.4.2. First maximum of the bench-index (*BI*)

The *BI* method provided larger mean reach estimates of bankfull stage than the minimum width-to-depth ratio on all study reaches, with a significant difference occurring on seven of the nine reaches (Table 3.2). The *BI* method performed less well against qualitative estimates than the *WD* method overall, with only three of the nine reaches rated satisfactory. However on the reaches where the performance of the *BI* method was satisfactory, *NSE*, *RSR* and *PBIAS* values were better than those of the *WD* method. The *BI* method provided bankfull stage values much higher than the estimated bankfull stage on some reaches, with *PBIAS* values ranging up to -56.84 % (Table 3.3). These results reflect those of previous studies which have found that the first maximum of the bench-index significantly overestimated bankfull stage on some reaches (Williams, 1978, Radecki-Pawlik, 2002, Navratil et al., 2004, Navratil et al., 2006). It should be noted however, that the use of modern software to model changes in channel morphology at very small increments makes comparisons with older studies where channel morphology changes were modeled using field surveyed data points only difficult. The BI method generally performed poorly where the channel had a sloping bank on one or both sides of the river channel breaking into a sloping floodplain and best where the channel banks were more perpendicular and the floodplain more horizontal (Figures 3.5 to 3.10).

Williams (1978) suggested that the bench-index method needed further development, and the results from this study highlight areas where improvements to the method could be focused. Firstly, a maximum of the *BI* other than the first often occurred at a stage equivalent to qualitative estimates of bankfull stage (Figure 3.11). The location of the first maximum of the bench-index is dependent on the upper limit of the cross-sectional profile to which it is applied (Riley, 1972), and in this study where plotted channel profiles extended well above the bankfull channel the first maximum often occurred at a stage well above the qualitative estimate of bankfull. A number of previous studies have also found that the first maxima corresponded with an elevation above bankfull (Navratil et al. 2004) and that maxima other than the first are equivalent to bankfull stage (Radecki-Pawlik, 2002, Navratil et al., 2006). This supports the views of Riley (1972) who suggested that subjective judgment may be required to define the traverse limits around the approximate bankfull channel to ensure the correct bench-index maxima is identified.

Secondly, bench-index maxima often occurred at an increment above qualitative estimates of bankfull stage. Maxima of the bench-index occur where there are large increases in width relative to increases in stage (Riley, 1972). In many of the cross-sections in this study, large increases in width occurred at the elevation immediately above the top of the channel bank (e.g. Figure 3.11), resulting in a large peak in the bench-index. As bankfull in this study was defined as the stage *above* which the flow exceeds the active channel banks, the increment prior (at a lower elevation) to a maximum of the bench-index was often equivalent to the best estimate of bankfull stage. Differences in elevation between these two stages were small (0.01 m), but near bankfull small increases in stage can result in large increases in other parameters (Gordon et al., 2004, Wilkerson, 2008). In this study a single 0.01 m increment in stage resulted in an increase in channel width of more than 3 m for some sites.

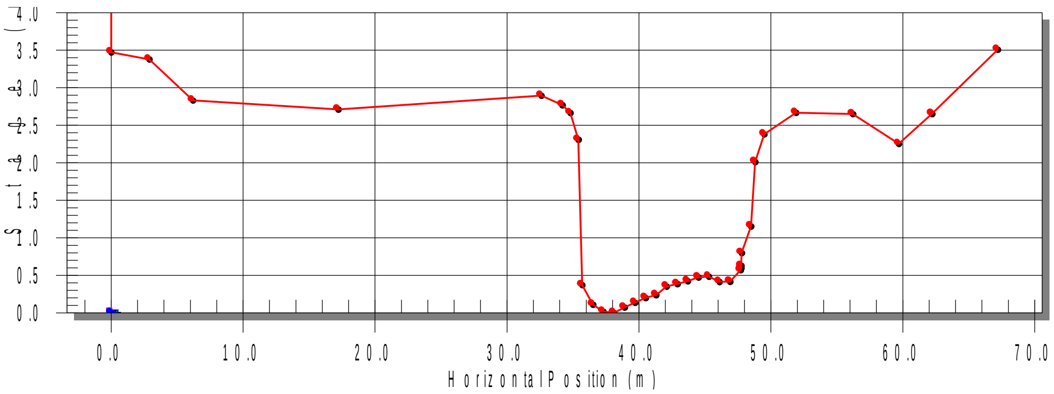


Figure 3.12. Cross-sectional channel plot for the Nile River at Nile. A flood chute is located approximately 10 m to the right of the main channel.

Table 3.4. Channel parameters for cross-section 7 at the Nile River at Nile calculated at 0.01 m intervals. Width-to-depth ratio (*WD*) and bench Index (*BI*) were determined using Equations 3.1 and 3.3 respectively. Best estimate of bankfull stage is in bold.

Stage (m)	Cross-sectional area (m2)	Wetted Perimeter (m)	Width (m)	*BI*	*WD*
2.63	31.97	25.28	22.41	25	15.46663
2.64	32.2	25.54	22.66	25	15.70873
2.65	**32.42**	**25.79**	**22.91**	**25**	**15.94645**
2.66	32.67	28.34	25.46	25	16.18964
2.67	32.93	30.43	27.54	255	19.84119
2.68	33.21	30.54	27.65	208	23.03224
2.69	33.49	30.66	27.77	12	23.02696

A channel cross-section from the Nile River at Nile, for example, had an estimated bankfull stage of 2.65 m with a width of 22.91 m, while the *BI* estimate of bankfull stage was 2.67 m with a width of 27.54 (Figure 3.12 and Table 3.4); an increase in stage of just 0.02 m resulting in a difference of 4.63 m in bankfull width. Estimated bankfull stage for this cross-section using *WD* was 2.68 m with a width of 27.65 m. These results reflect the particular geometry of the channel at this location, where discharge at around bankfull levels resulted in the channel becoming connected with the floodplain via a floodchute (Figure 3.12)

3.4.3. Reach variability and definitions of bankfull stage

3.4.3.1. Reach variability

There was no clear relationship between the success or failure of *WD* or *BI* estimates and the river style, or reach variability and river style (Table 3.1 and 3.3). However to investigate the possible influence of landscape setting on bankfull stage estimation and bankfull stage variability further, three sites were examined in more detail.

The Third River at Paling Track is a partially confined upstream site set in a landscape of moderately steep hills, ridges and spurs with flat alluvial valleys in many areas. The relatively small stream merges with the Pipers River before discharging to the north coast of Tasmania. It had the highest *CV* for *BF* estimates along a reach for all sites (Table 3.3). The *WD* method was assessed to have performed satisfactorily on this reach, while *BI* performance was assessed as unsatisfactory. *BI* performed poorly on those cross-sections which had sloping channel banks and best where the channel banks were more vertical (Figures 3.5 and 3.6).

The Nile River at Nile is an unconfined reach set in a low relief landscape, composed of broad valleys on Tertiary sediment. It is located around 4 km upstream of the confluence of the Nile with the South Esk River, which goes on to discharge into the Tamar Estuary. The site has poor riparian vegetation. The reach experiences reasonably high stream power values as the slope here is quite high (0.005 m/m). It had a low *CV* along a reach for all three methods of estimating bankfull stage, but significant differences existed between mean reach estimates of *WD* and *BI*. *WD* estimates performed satisfactory against *BF* estimates, but *BI* fell outside satisfactory model performances.

The Isis River at Isis is an unconfined channel set in a low relief landscape, composed of broad valleys on Tertiary sediments. There is little riparian vegetation along the channel banks and stock have unrestricted access to the river. The channel along this reach is highly variable and quite complex, with a well developed flood chute or smaller secondary channel present in some parts. Stream power is relatively small at this reach due to the low slope. It had quite a high *CV* for *BF*, and both *WD* and *BI* model performances were outside satisfactory model performances.

Previous studies had suggested that rivers draining to the north coast had low hydrological variability resulting in more homogenous reach morphology than other rivers (DPIPWE, 2010). This relationship was not found in the results of this study, with the north draining Great Forester and Ringarooma rivers showing high and medium variability respectively. However as rivers can vary greatly longitudinally, the lack of a relationship in this study may simply be the result of sampling variability, and further study is required to make any conclusions in this regard.

There was no obvious pattern in the variability associated with valley setting river type, with both the two highest and two lowest levels of variability along a reach belonging to partially confined reaches (Table 3.1). The similarity in the patterns of coefficient of variation (*CV*) variability between sites and along a reach (Figures 3.6, 3.8 and 3.10) for each of the three methods suggest that it is a result of natural variability rather than model error or bias, while the high individual *CV* values for all estimates of bankfull stage along a reach (*WD*, *BI* and *BF*) (Table 3.3) strongly support the view that bankfull stage should be defined as a range of values rather than as a single number related strictly to the geometry of a particular cross-section (Radecki-Pawlik, 2002).

3.4.3.2. Defining bankfull stage

Based on the results of this study, two suggestions are made in regard to the definition of bankfull stage. Firstly, bankfull stage should be reported as a mean reach value. The high variability in bankfull stage estimates along a reach found in this and other studies indicate that an individual cross-section has little meaning in relation to bankfull stage.

Secondly, the results suggest that bankfull stage should be reported as a range of values. This study has found that small increments in stage can bring about significant variability in process responses such as within-channel and channel-floodplain linkages. Near bankfull level, a very small increment in stage can result in significant differences in the width of the water surface as discharge in the main channel becomes connected with the floodplain. In the typical irregular channel morphology, this may mean the river channel being connected with the floodplain via smaller flood chutes at some points along the reach, while discharge is still constrained within the river banks at other points on the same reach. An example of this can be seen in the image of the North Esk River at bankfull stage flood (Figure 3.13). Prior to bankfull stage, discharge is constrained within the river channel banks. As discharge nears bankfull stage, discharge overflows the banks at the lowest points along the reach, flowing into flood chutes which direct the discharge onto the floodplain. Even after the flood chutes have substantial flow, the reach channel banks constrain the discharge to the main channel at many points.

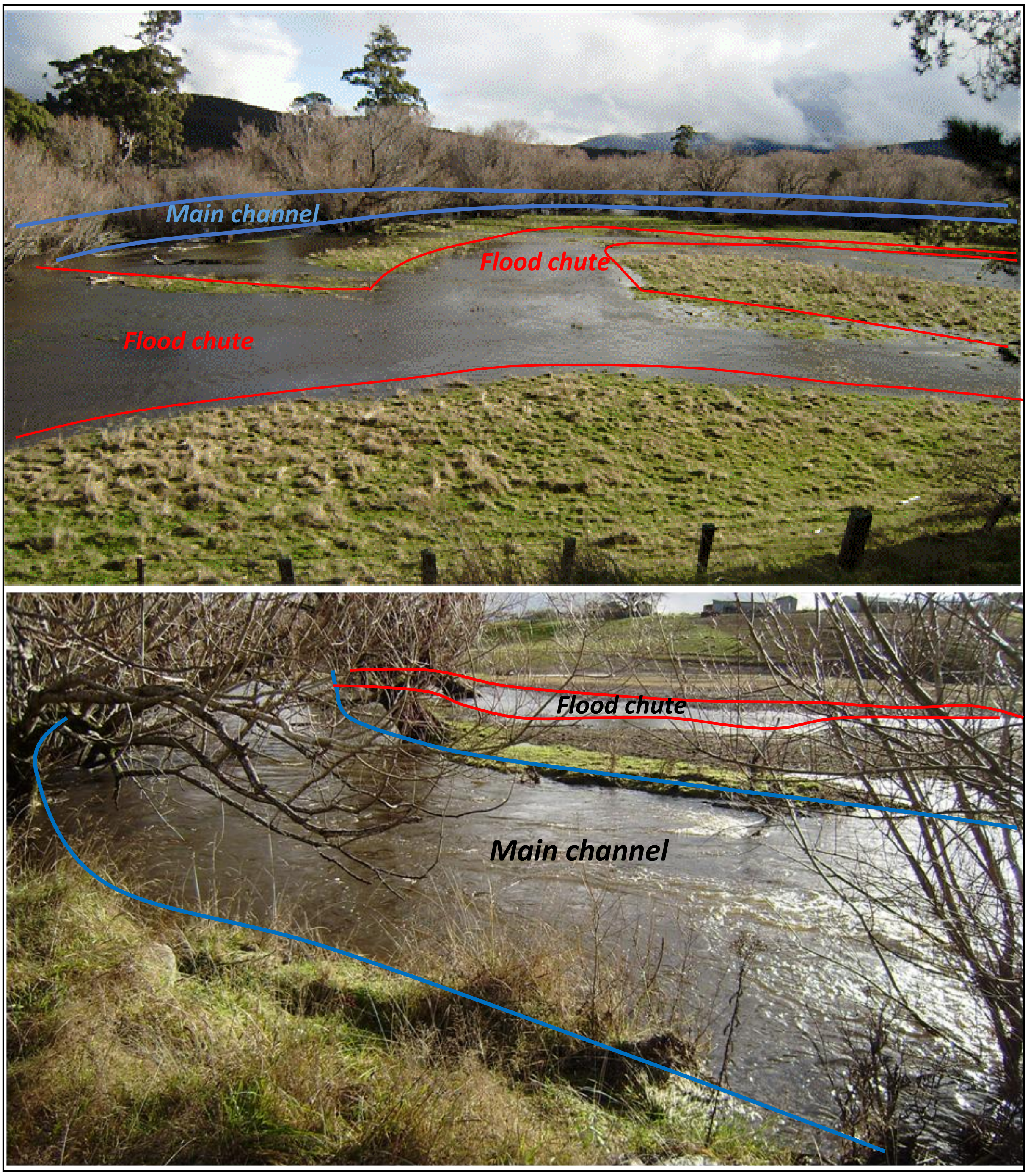


Figure 3.13. Flood chutes that become active during bankfull discharge connecting different sections of the main channel of the North Esk River while discharge remains within channel banks at other sections. The obstruction of the main channel by willows results in flood chutes becoming active during smaller flood events.

Johnson and Heil (1996) suggested the use of fuzzy sets, where fuzzy numbers are used to express vagueness and subjectivity, to describe bankfull stage. However this method is based on subjective judgement and is more suited to situations where there are multiple lines of evidence. Others have suggested that bankfull stage is a transition zone extending from the point of bank inflection to the top of bank elevation (Navratil et al., 2006) and should be presented as a range of values (Johnson and Heil, 1996, Radecki-Pawlik, 2002). However this method does not provide any measure of the sampling variability inherent in estimating bankfull stage.

Based on the results from this study, it is suggested that bankfull stage be reported as a mean reach value, as values determined from a single cross-section are meaningless. Associated with this, full definitions and methods should also be provided. Finally, it is suggested that bankfull stage be defined using a maen reach value with confidence intervals. Confidence intervals express is a range that we expect, with some level of confidence, to include the actual value of population mean. Confidence intervals take into account the sample size as well as the variability (standard deviation) of the sample. It is therefore recommended that estimates of mean bankfull stage are reported with confidence intervals (generally 95%) as well as the number of observations used. It is also recommended that the suggestion of Navratil (2006) that the bankfull definitions used should also be specified in detail is followed when reporting bankfull stage estimates. As an example, the estimated mean bankfull stage for The Nile River at Nile, using the definition of Riley (1972) is 2.54 m, n = 12, 95% CI [2.30, 2.77].

However it should also be remembered that confidence intervals only communicate uncertainty associated with sampling error and cannot describe or control non-sampling error (Walshe et al. 2007). Any method not using complex statistical techniques will necessary include uncertainty based on sample representativeness, observer or method error, measurement error (Tayfur and Singh, 2011).

3.5. Conclusion

The two most frequently used quantitative methods for determining bankfull stage were evaluated on 89 channel cross-sections across eight rivers in north-eastern Tasmania across a range of channel sizes and cross-sectional shapes. The evaluation measures used in this study suggested that neither the minimum width-to-depth ratio nor the first maximum of the bench-index provide a satisfactory accurate, objective and repeatable method to determine bankfull stage from plotted channel geometries across all study reaches.

The minimum width-to-depth ratio provided lower mean reach values of bankfull stage than the first maximum of the bench-index for all sites, and generally provided lower values than qualitative estimates of bankfull stage, but was the best performed of the two models overall when assessed against qualitative estimates. These results support previous studies that suggest the minimum width-to-depth ratio approximates to the stage above which increases in width becomes more rapid than increases in mean depth (Harvey, 1969), rather than identifying bankfull stage. They also suggest that the performance of this method may be dependent on channel shape. The first maximum of the bench-index provided larger values than qualitative estimates of bankfull stage on all reaches and generally performed less well when compared against qualitative estimates than the minimum-width-to-depth ratio. It performed best when channel banks were relatively perpendicular and there was a clean break to a horizontal floodplain. The results from this study also suggest that the accuracy of the bench-index method may be significantly improved by either limiting the range of analysis to the approximate bankfull stage or considering maximum other than the first, and by equating bankfull stage with the increment below maxima of the bench-index. Although these results support views that there is no precise analytical method for determining bankfull value (Radecki-Pawlik, 2002), they also suggest that these two methods provide a useful adjunct in the subjective determination of bankfull stage, as the 'true' value generally lies between the values provided by these two methods.

The high variability in bankfull stage estimates along a reach found in the study, along with the differences between methods, suggests that where possible bankfull stage should be considered at the reach rather than cross-sectional scale, and that bankfull stage parameters should be presented as a range of values with associated confidence intervals rather than as a finite result. The number of samples used in the study and the definition of bankfull stage used should also be reported.

References

BOUWMAN, A., BIERKENS, M., GRIFFIOEN, J. & HEFTING, M. M. 2013. Nutrient dynamics, transfer and retention along the aquatic continuum from land to ocean: towards integration of ecological and biogeochemical models. *Biogeosciences,* 10**,** 1-22.

BROOKS, A. & Brierley, G. 2002. Mediated equilibrium: The influence of riparian vegetation and wood on the long-term evolution and behaviour of a near-pristine river. *Earth Surface Processes and Landforms*, 27(4), 343-367.

CANTY, A. & RIPLEY, B. 2014. boot: Bootstrap R (S-Plus) Functions. R package version 1.3-11 ed.

COHEN, T. & HOUSHOLD, I. 2005. An introduction to river processes and river rehabilitation in Tasmania. DPIW.

COPELAND, R. R., BIEDENHARN, D. S. & FISCHENICH, J. C. 2000. Channel-forming Discharge. *US Army Corps of Engineers Technical Note.*

DE ROSE, R. C., STEWARDSON, M. J. & HARMAN, C. 2008. Downstream hydraulic geometry of rivers in Victoria, Australia. *Geomorphology,* 99**,** 302-316.

DICICCIO, T. J. & EFRON, B. 1996. Bootstrap Confidence Intervals. *Statistical Science,* 11**,** 189-212.

DOYLE, M., SHIELDS, D., BOYD, K., SKIDMORE, P. & DOMINICK, D. 2007. Channel-Forming Discharge Selection in River Restoration Design. *Journal of Hydraulic Engineering,* 133**,** 831-837.

DPIPWE 2010. Tasmanian Environmental Flows (TEFlows) Project Technical Report. *Water Assessment Aquatic Ecology Report Series.* Hobart, Tasmania: Water and Marine Resources Division, Department of Primary Industries, Parks, Water and Environment,.

DUNNE, T. & LEOPOLD, L. B. 1978. *Water in environmental planning,* San Francisco, W.H. Freeman and Company.

DURY, G. H., HAILS, J. R. & ROBBIE, M. B. 1963. Bankfull discharge and the magnitude frequency series. *Australian Journal of Science,* 26**,** 123-124.

DUTTA, D., HERATH, S. & MUSIAKE, K. 2003. A mathematical model for flood loss estimation. *Journal of Hydrology,* 277**,** 24-49.

FINLAYSON, B. L. & MCMAHON, T. A. 1988. Australia v the World: A comparitive analysis of streamflow characteristics. *In:* WARNER, R. F. (ed.) *Fluvial Geomorphology of Australia.* Sydney: Academic Press.

FOX-HUGHES, P. 2009. A heavy rainfall event in Northern Tasmania during 27 to 30 January 2004. *Australian Meteorological and Oceanographic Journal* 58**,** 151-166.

GIPPEL, C. 1985. Changes in stream channel morphology at tributary junctions, Lower Hunter Valley, New South Wales. *Australian Geographical Studies,* 23**,** 291-307.

GOMEZ, B., COLEMAN, S. E., SY, V. W. K., PEACOCK, D. H. & KENT, M. 2007. Channel change, bankfull and effective discharges on a vertically accreting, meandering, gravel-bed river. *Earth Surface Processes and Landforms,* 32**,** 770-785.

GORDON, N. D., MCMAHON, T. A., FINLAYSON, B. L., GIPPEL, C. J. & NATHAN, R. J. 2004. *Stream hydrology : an introduction for ecologists* Chichester, West Sussex, Wiley.

GRANT, G. E., DUVAL, J. E., KOERPER, G. J. & FOGG, J. L. 1992. XSPRO: A Channel Cross-Section Analyzer. Technical Note 387, BLM/SC/PT-92/001+7200 ed. Denver, CO: USDI Bureau of Land Management and USDA Forest Service.

GREGORY, K. J. 1976. Drainage networks and climate. *In:* DERBYSHIRE, E. (ed.) *Geomorphology and Climate.* London: John Wiley and Sons.

GUPTA, H. V., SOROOSHIAN, S. & YAPO, P. O. 1999. Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *Journal of Hydrologic Engineering,* 4**,** 135-143.
HARMAN, C., STEWARDSON, M. & DEROSE, R. 2008. Variability and uncertainty in reach bankfull hydraulic geometry. *Journal of Hydrology,* 351**,** 13-25.
HARVEY, A. M. 1969. Channel capacity and the adjustment of streams to hydrologic regime. *Journal of Hydrology,* 8**,** 82-98.
HE, L. & WILKERSON, G. V. 2011. Improved Bankfull Channel Geometry Prediction Using Two-Year Return-Period Discharge. *Journal of the American Water Resources Association*.
INSTITUTION OF ENGINEERS AUSTRALIA 1987. Australian Rainfall and Runoff: A Guide to Flood Estimation. Canberra.
JOHNSON, P. A. & HEIL, T. M. 1996. Uncertainty in estimating bankfull conditions. *Journal of the American Water Resources Association,* 32**,** 1283-1291.
KNIGHTON, D. 1998. *Fluvial Forms and Processes: A new perspective,* London, Arnold.
LEOPOLD, L. B., WOLMAN, G. M. & MILLER, J. P. 1964. *Fluvial Processes in Geomorphology,* San Francisco, W.H. Freeman and Co.
MCCUEN, R. H., KNIGHT, Z. & CUTTER, A. G. 2006. Evaluation of the Nash-Sutcliffe efficiency index. *Journal of Hydrologic Engineering,* 11**,** 597-602.
MORIASI, D. N., ARNOLD, J. G., VAN LIEW, M. W., BINGNER, R. L., HARMEL, R. D. & VEITH, T. L. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the Asabe,* 50**,** 885-900.
NAVRATIL, O., ALBERT, M. B., BOUDARD, C. & GRESILLON, J. M. 2004. Using a 1D steady flow model to compare field determination methods of bank-full stage. *In:* GRECO, M., CARRAVETTA, A. & DELLA MORTE, R. (eds.) *River Flow 2004.* London: Taylor and Francis Group.
NAVRATIL, O., ALBERT, M. B. & BREIL, P. 2010. Test of three methods to detect the overbank flow from water level time-series analysis. *Hydrological Processes,* 24**,** 2452-2464.
NAVRATIL, O., ALBERT, M. B., HÉROUIN, E. & GRESILLON, J. M. 2006. Determination of bankfull discharge magnitude and frequency: comparison of methods on 16 gravel-bed river reaches. *Earth Surface Processes and Landforms,* 31**,** 1345-1363.
NRM SOUTH 2009. Tasmanian River Condition Index Reference Manual. Hobart: NRM South.
PAGE, K. J. 1988. Bankfull discharge frequency for the Murrumbidgee River, New South Wales. *In:* WARNER, R. F. (ed.) *Fluvial geomorphology of Australia.* Sydney: Academic Press.
PICKUP, G. 1976. Alternative measures of river channel shape and their significance. *Journal of Hydrology New Zealand,* 15**,** 9-16.
PICKUP, G. & WARNER, R. F. 1976. Effects of hydrologic regime on magnitude and frequency of dominant discharge. *Journal of Hydrology,* 29**,** 51-75.
RADECKI-PAWLIK, A. 2002. Bankfull discharge in mountain streams: Theory and practice. *Earth Surface Processes and Landforms,* 27**,** 115-123.
RICHARDS, K. S. 1982. *Rivers, Form and Process in Alluvial Channels,* Taylor and Francis.
RILEY, S. J. 1972. A comparison of morphometric measures of bankfull. *Journal of Hydrology,* 17**,** 23-31.
ROSGEN, D. L. 1994. A classification of natural rivers. *CATENA,* 22**,** 169-199.
ROSGEN, D. L. 2009. Discussion-"The Role of Observer Variation in Determining Rosgen Stream Types in Northeastern Oregon Mountain Streams" by Brett B. Roper, John M.

Buffington, Eric Archer, Chris Moyer, and Mike Ward. *JAWRA Journal of the American Water Resources Association,* 45**,** 1290-1297.
SHARPLES, C. 1996. The geology and landforms of northeast Tasmania.
SIMON, A., DICKERSON, W. & HEINS, A. 2004. Suspended-sediment transport rates at the 1.5-year recurrence interval for ecoregions of the United States: transport conditions at the bankfull and effective discharge? *Geomorphology,* 58**,** 243-262.
STREAM SYSTEMS TECHNOLOGY CENTRE 1993. Would the real bankfull please stand up. *Stream notes*.
TAYFUR, G. & SINGH, V. 2011. Predicting Mean and Bankfull Discharge from Channel Cross-Sectional Area by Expert and Regression Methods. *Water Resources Management*, 25(5), 1253-1267.
TOOTH, S. & NANSON, G. C. 1995. The geomorphology of Australia's fluvial systems: retrospect, perspect and prospect. *Progress in physical geography,* 19**,** 35-60.
WALSHE, T., WINTLE, B., Fidler, F. & BURGMAN, M. 2007. Use of confidence intervals to demonstrate performance against forest management standards. *Forest Ecology and Management*, 247 (1), 237-245.
WILKERSON, G. V. 2008. Improved bankfull discharge prediction using 2-year recurrence-period discharge. *Journal of the American Water Resources Association,* 44**,** 243-258.
WILLIAMS, G. P. 1978. Bank-full discharge of rivers. *Water Resour. Res.,* 14**,** 1141-1154.
WOHL, E. 2010. *Mountain rivers revisited*, American Geophysical Union.
WOLMAN, M. G. 1955. The natural channel of Brandywine Creek, Pennsylvania. . *US Geological Survey Professional Paper.*
WOLMAN, M. G. & LEOPOLD, L. B. 1957. River flood plains: some observations on their formation. *US Geological Survey Professional Paper.* Washington.
WOLMAN, M. G. & MILLER, J. P. 1960. Magnitude and frequency of forces in geomorphic processes. *Journal of Geology,* 68**,** 54-74.
WOODYER, K. D. 1968. Bankfull frequency in rivers. *Journal of Hydrology,* 6**,** 114-142.

Chapter 4 The relationship between discharge and catchment area for north-eastern Tasmanian rivers using annual and partial series data

Abstract: This study developed power law equations relating the peak discharge of floods with average recurrence intervals ranging from 1.1 to 10 years to catchment area. Data from 13 streamflow stations in north-eastern Tasmania were used to derive annual and partial series datasets. Flood frequency analysis was conducted on each dataset to provide partial series and annual series flood frequency estimates, which were then used to develop power-law equations linking discharge to catchment area using least squares linear regression of log transformed variables. The coefficients in the regression equations developed using flood frequency estimates based on annual series data were then compared with those based on partial series data sets, with a null hypothesis that there is no significant difference between the coefficients. The results of this study were also compared with those from other studies and intra-regional variation in the relationship between discharge and catchment area was investigated. Results showed that values of regression coefficient *b* were mostly in the range of 0.89 to 0.92, which is similar to values found previously in Tasmanian and elsewhere. No significant difference was found between the value of coefficient *b* determined using annual series flood frequency estimates and that developed using partial series flood frequency estimates, however a significant difference was found between the log of coefficient a developed using the different data series for *T* = 1.1, 1.5 and 2 years.

4.1. Introduction

The estimation of small floods in ungauged locations is a frequent problem for hydrologists, engineers, geomorphologists and ecologists. Amongst many other uses, estimates of the magnitude of small floods are required for infrastructure design (Alexander, 1972), river restoration projects (Wilkerson, 2008) and flood loss mitigation (Kreibich et al., 2005). A variety of methods are used to estimate discharge at ungauged sites, and most involve the use of catchment area. Catchment area is adopted as a proxy for discharge on the assumption that it is the main scaling factor in the flood process and that it directly affects the potential flood magnitude from a given storm event (Rahman et al., 2009). Simple empirical relationships between discharge and catchment area have been proposed since at least the 1860's (Alexander, 1972), and the close relationship between these two parameters has since been extensively demonstrated. In a study of annual series data from thirteen streamflow stations in north-eastern Tasmania, Knighton (1987) found a correlation greater than 97% between mean annual discharge and catchment area, despite less uniform patterns of rainfall there than in other areas where similar relationships had been found. Most catchment characteristics are correlated with catchment area (Haddad et al., 2011), and catchment area is the most common parameter used in regional hydrological modelling (Lima and Lall, 2010).

The power-law relationship between discharge and catchment area is a frequently used method for providing first order estimates of discharge for a wide range of hydrologic and engineering purposes relating to watershed management (Galster, 2007). The general procedure is to pool data from a number of stream gauging stations in a hydrologically homogenous region to produce a form of the general empirical relationship:

$$Q_T = aA_d^b \tag{4.1}$$

where Q_T is the peak discharge of a flood with an average recurrence interval equal to T years, A_d is the upstream drainage or catchment area (km^2), a is the theoretical discharge per unit of catchment area (m^{3}s^{-1}), and the exponent b is a scaling factor that has been found to have a narrow range for a given frequency of flow (specific Q_T) across a large range of catchment areas (Knighton, 1999). The power-law relationship is found in a diverse range of natural phenomena (Hui and Jackson, 2007, Clauset et al., 2009, Xiao et al., 2011), including hydrological phenomena (Malamud and Turcotte, 2006).

As well as a means of estimating discharge at ungauged locations, the discharge-catchment area power-law relationship can also provide information about intra-regional variations in hydrology (Gupta and Dawdy, 1995). Comparing individual sites against regional trends can identify inter-basin contrasts in flood generation and transmission (Knighton, 1987), and changes in the relationship can provide information on how watershed hydrology is evolving or changing in response to natural or anthropogenic changes (Galster, 2007). However, variations in power-law relationships may also be due to factors such as sample size, measurement error and analysis method (Hui and Jackson, 2007). A great deal of study has focused on the type of regression model employed, and although previous analyses based on log-transformation have been found to be generally valid (Xiao et al., 2011), debate continues on the use of traditional linear regression of log transformed variables versus non-linear regression of untransformed variables (Clauset et al., 2009). Much less attention has been directed towards the impact of sampling error and measurement error on the relationship. Sampling error arises when the study sample is not representative of the actual population, and can generally be reduced by increasing the sample size. In this study however, the sample size is necessarily limited to existing streamflow records. Measurement error (or observational error) is the difference between the measured value of a parameter and the true value. Discharge is more susceptible to measurement error than catchment area, as while estimates of catchment area are generally easily obtained (He and Wilkerson, 2011), and reliable (Lima and Lall, 2010), the estimation of discharge generally involves a number of areas of uncertainty and error.

Discharge is estimated at stream gauging stations through flood frequency analysis of the stream flow record, with the choice of probability distribution and parameter estimation method common areas of uncertainty. However choices must also be made on the method used to subsample a dataset on which the analysis is to be undertaken. There are two main methods: the annual maximum series, also known as the annual series, uses the single peak flood event from each year of the streamflow record, while the partial series, also known as peaks-over-threshold (POT), is composed of all discharges over a chosen threshold for the entire streamflow record. Because the annual maximum series may exclude substantial floods if they are not the largest of the year and include small annual maximums that are not really flood events, flood frequency analysis based on the annual series has been shown to underestimate the magnitude of small floods (Page and McElroy, 1981, Institution of Engineers Australia, 1987, Armstrong et al., 2012, Keast and Ellison, 2013) (Chapter 2).

Despite this, and due at least in part to the ease with which the annual series is defined in comparison to the partial series, flood frequency quantiles for the power law relationship between discharge and catchment area are commonly estimated using the annual series. Literature searches indicate that there have been no previous studies on the impact of flood data series choice on the estimation of the coefficients in discharge-catchment area power-law equations.

4.1.1. Aim and purpose

The purpose of this study was to provide first order estimates of discharge at ungauged sites in north-eastern Tasmania. The aim of this study was to develop regional discharge-catchment area power-law relationships using both annual series and partial series data sets.

4.1.2. Study area

Tasmania is the southernmost state of Australia, with the main island extending across a latitudinal range of 39° 40′ to 43° 20′ S. The north-eastern region of Tasmania covers more than 6,500 km^2, almost one-third of the State's landmass (Figure 4.1), and is roughly delineated by the Tamar Estuary in the west and the Fingal Valley in the south. Tasmania is commonly divided into two distinct hydrological regions, the eastern and western, based on rainfall regimes (McConachy et al., 2003, Fox-Hughes, 2009, Haddad et al., 2011), with the study region falling wholly within the eastern region. However, within these broad categories considerable intra-regional variation in hydrology exists. Precipitation is largely controlled by topography and ranges from an annual average of less than 700 mm in low lying and coastal areas up to more than 1,200 mm in the highlands (Bureau of Meteorology, 1993). Steep precipitation gradients exist in some areas and occasional very heavy rainfall events associated with the passage of intense low pressure systems cause localised flooding in some areas of the region (Fox-Hughes, 2009). Geology, soils, vegetation and geomorphology also vary throughout the region.

4.2. Methods

4.2.1. Data

Stream-flow data for the thirteen streamflow gauging stations listed in Table 4.1 were obtained from the Tasmanian Department of Primary Industries, Parks, Water and the Environment (DPIPWE). These gauging stations are located on a variety of stream types and distributed throughout north-eastern Tasmania (Figure 4.1). Accumulated catchment area for each station listed in Table 4.1 was determined from the Tasmanian Conservation of Freshwater Ecosystem Values (CFEV) (DPIPWE, 2005) data set which is based on a 1:25 000 drainage network data layer derived from a 25 m digital elevation model (DPIW, 2008).

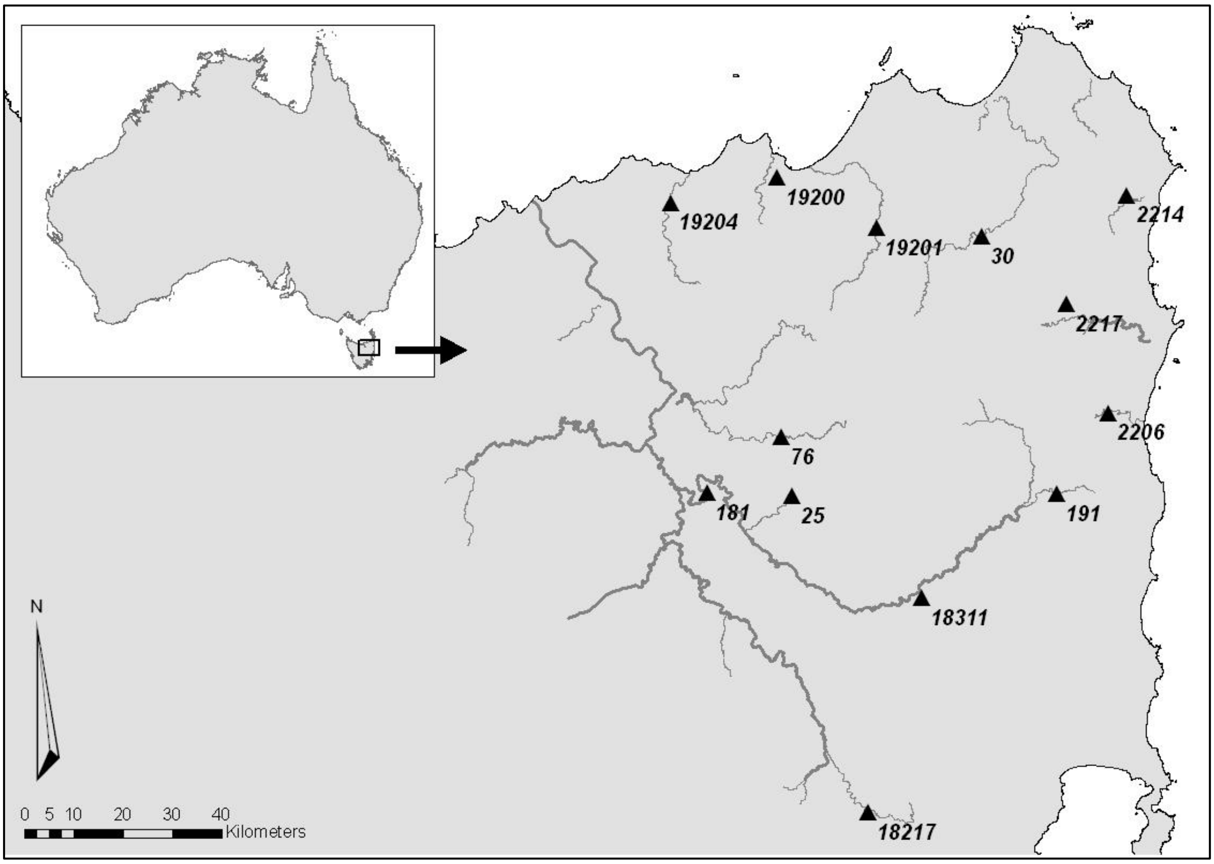


Figure 4.1. Major rivers of north-eastern Tasmania and the location of streamflow stations used in this study. State Government stream-gauge codes are used to identify sites (See Table 4.1).

Table 4.1. Stream gauging sites and flow records used in the flood frequency analyses. Those indicated by * were also included in the study by Knighton (1987).

Site Number	DPIPWE Code	Site Name	Years of record (*n*)	Catchment area (km^2)
1	2214	Ansons River downstream of Big Boggy Creek	10	228.9
2	191	Break O'Day River at Killymoon	28	186.2
3	19200	Brid River 2.6 km upstream of tidal limit*	34	138.9
4	19201	Great Forester River 2 km upstream of Forester Road*	41	192.0
5	18217	Macquarie River at Trefusis	32	375.3
6	76	North Esk River at Ballroom*	85	375.9
7	25	Nile River at Deddington	10	220.9
8	19204	Pipers River downstream of Yarrow Creek*	39	298.4
9	30	Ringarooma River upstream of Moorina Bridge*	34	482.3
10	2217	Ransom River at Sweet Hills*	28	26.4
11	2206	Scamander River upstream Scamander water intake	10	268.0
12	181	South Esk River above Macquarie River	55	3306.4
13	18311	St. Pauls River upstream of South Esk River	23	524.2

4.2.2. Flood frequency analysis

The procedures for flood frequency analysis generally followed those described in Keast and Ellison (2013). Annual series data sets were created for each site by time stepping daily streamflow data to annual maxima. A two-parameter Log-Normal distribution was then fitted to each data set using Bayesian Markov Chain Monte Carlo (BMCMC) parameter estimation. These methods have previously been found to be the best performing flood frequency distribution and associated parameter estimation procedure for Tasmanian annual series flood data (Rahman et al., 2009). The procedure was performed in this study using the BaysesianMCMC function of the nsRFA package in R, with each algorithm iterated 5000 times (Viglione, 2009).

Partial series data sets were created from daily streamflow data using the cluster function of the POT Package (Ribatet, 2011) in R, with fourteen days between flood events used as a criterion for ensuring the independence of successive flood peaks. Thresholds were adjusted so that the number of flood events (k) was 1.5 - 2.5 times the number of years of record (n) (Table 4.2), with the value varied to optimize the fit of the distribution to the observed data. It should be noted that partial series magnitude estimates were generally closely clustered, regardless of the number of flood events included. The IEA (Institution of Engineers Australia, 1987) suggest that graphical interpolation is sufficiently accurate when using the partial series where $T < 10$ years, however due to the relatively short length of record at some sites, a probability distribution was also fitted to the observed data. The Generalized Pareto Distribution (GPD) has been widely used for flood frequency analysis with partial series data (e.g. Madsen et al., 1997, Adamowski et al., 1998, Mohssen, 2009), and a three parameter GPD was fitted to each of the thirteen partial series data sets. The parameters of the GPD were estimated using a maximum likelihood approach via the fitgpd function of the POT Package (Ribatet, 2011).

The fit of each Log-Normal distribution (annual series) and GPD (partial series) was checked visually using histograms and quantile-quantile (QQ) plots and the fitted distributions were also verified against the original data on log-log plots. Plotting positions for the observed peak discharges were determined following the general recommendations of Cunnane (1978), Nanson (2008) and Institution of Engineers Australia (1987) using the equation:

$$T = \frac{[(n+1) - 2 \propto]}{(m - \propto)} \tag{4.2}$$

where m is the rank of each event and α is a bias constant. The bias constant adjusts plotting positions to account for the dataset being a sample of the real population and was set at 0.4 in this study following the example of previous flood frequency analysis studies in Eastern Australia (Rustomji, 2009). Using these procedures, at-site flood frequency quantiles were estimated for each station for T = 1.1, 1.5, 2, 2.33, 3 4, 5 and 10 years using both annual series and partial series data.

4.2.3. Regression analysis

Regression analysis was used to examine the relationship between the dependant variable discharge, and the independent variable catchment area, for the sixteen data sets (eight annual and eight partial). Following general practice both discharge and catchment area was log transformed prior to analysis to produce a linear form of Equation 4.1.

$$\log(Q_T) = \log(a) + b\log(A_d) + (\varepsilon) \tag{4.3}$$

A least-squares linear regression was then undertaken on the log-transformed datasets, producing variations of the general power-law model shown in Equation 4.1. The resulting equations were graphed on log transformed axes, such that the intercept on the y-axis represents the coefficient (a) of the power-law in equation 1 and the slope of the linear regression in the plot represents the exponent (b). Although this method can generate significant systematic errors under relatively common conditions (Clauset et al., 2009), it is still widely used, and results determined using this method have been found to be generally valid (Xiao et al., 2011). A weighted least squares (WLS) regression was considered for the analysis due to the small number of observations used. However, uncertainty in the WLS weightings caused by the large variation in both the length and quality of the streamflow records and the large differences in catchment area between the largest and smallest stations meant this method was rejected. Each regression model was assessed using diagnostic plots. These included standard quantile-quantile plots, scale-location plots, and Cook's distance plots to assess the influence of individual observations. To compare the fit of the log - transformed variables to a normal distribution, normal probability plots of the standardized residual (the residual divided by its standard deviation) were also produced and are presented in Appendix 4.1. These plots compare the distribution of the error against the normal distribution (the diagonal line) for each regression.

4.2.4. Comparison of regression coefficients

An analysis of covariance (ANCOVA) was undertaken to determine if there was a significant difference between the slopes of the regression relationships developed using annual series data (b_1) with those developed using partial series data (b_2). ANCOVA uses a combination of regression and analysis of variance (ANOVA) to control differences between groups based on another variable called the covariate. If an ANCOVA has a significant interaction between the categorical and quantitative explanatory variables, then the slope of the equation relating the quantitative variable to the outcome differs for different levels of the categorical variable. ANCOVA was first used to check for interaction between the covariate (whether the data type is annual or partial) and quantitative (peak discharge and catchment area) explanatory variables (H_0: $b_1 = b_2$). Where no interaction existed (i.e. no significant difference), an ANOVA without interaction was then used to determine if there was a significant difference between the log of the power-law coefficient developed using annual series flood frequency estimates ($\log(a_1)$) with the log of those developed using partial series estimates ($\log(a_2)$) (H_0: $\log(a_1) = \log(a_2)$).

4.3. Results

Details of the POT analyses for each individual site, which provided the partial series data sets for the study, are provided in Appendix 4.1. The POT analyses produced partial series datasets that consisted of independent flood peaks, with datasets ranging between 15 and 170 flood events. The threshold of the minimum discharge for partial series datasets ranged from 2.4 to 146 m^3s^{-1}. The log-normal and Generalized Pareto probability distributions generally provided good fits to the observed annual and partial series data respectively, and there was a close correlation between estimates from the fitted distribution flood quantiles and those derived from plots of the observed data. Full partial and annual series flood frequency estimates for all sites across all recurrence intervals are presented in Appendix 4.1.

The power-law coefficient and exponent, as well as the basic descriptive statistics from the related linear least squares regression analysis, for the relationship between log discharge and log catchment area, using both annual and partial series flood frequency estimates, are listed in Table 4.2, and plots of the relationships are provided in Figure 4.2. There was a significant positive relationship between log discharge and log catchment area for both annual and partial series flood frequency estimates across all average recurrence intervals (T = 1.1, 1.5, 2, 2.33, 3, 4, 5 and 10 years) at a 0.001 level of significance (df = 11) (Table 4.3). For annual series estimates, catchment area explained between 61% (T = 10 years) and 82% (T = 1.5 years) of the variation in discharge, with a general trend for R^2 values to decrease at average recurrence intervals above T = 1.5 years. The base flow (a) ranged from 0.12 to 0.81 m^3s^{-1}, and increased as average recurrence interval increased (Table 4.2 and Figure 4.3a). The rate of discharge (b) increased ranged from 0.84 to 0.93 (mean = 0.89), and also increased as average recurrence interval increased (Table 4.2 and Figure 4.3b). The standard error of the regressions (RSE), which is the root-mean-squared error adjusted for degrees of freedom, ranged from 0.454 (T = 1.5 years) to 0.821 (T = 1.5 years). Table 4.2 also shows the real space relative root mean square error (RRMSE) calculations in %, as Log space error statistics can provide a distorted view overall of the error. RRMSE was determined using Equation 4.4:

$$\mathrm{RRMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{Q_{pred} - Q_{obs}}{Q_{obs}}\right)^2} \times 100 \tag{4.4}$$

Where Q_{pred} is the annual series estimates and Q_{obs} is the partial series estimate (Table 4.2). RRMSE ranged from 12.56% to 25.4% for annual series estimates and from 7.70% to 27.04% for partial series estimates. RRMSE was lower for partial series estimates at T = 1.5 to T = 4 years, and was lower for annual series estimates for T = 1.1, 5 and 10 years.

Table 4.2. Summary of discharge-catchment area power-law relations for both annual and partial series flood frequency estimates using standard linear regression of log-transformed variables (*df* =11, $P < 0.001$). T = flood with an average recurrence interval of T years, a = regression coefficient, b = regression exponent, RSE = residual standard error of the log discharge-log area regression, RRMSE = real space relative root mean square error in percent. Note T = 2.33 years is commonly used as mean annual maximum flood.

T	**Annual**					**Partial**				
	a	***b***	R^2	**RSE**	**RRMSE**	***a***	***b***	R^2	**RSE**	**RRMSE**
1.1	0.12	0.84	0.748	0.602	12.56	0.34	0.89	0.745	0.571	13.59
1.5	0.23	0.87	0.818	0.454	19.02	0.40	0.90	0.723	0.608	7.70
2	0.32	0.89	0.809	0.476	17.38	0.45	0.90	0.714	0.632	14.87
2.33	0.36	0.89	0.791	0.506	21.54	0.47	0.91	0.708	0.643	11.38
3	0.43	0.90	0.758	0.561	19.36	0.51	0.91	0.701	0.659	14.80
4	0.52	0.90	0.720	0.623	22.56	0.55	0.92	0.693	0.676	14.74
5	0.59	0.91	0.688	0.676	19.81	0.58	0.92	0.686	0.690	20.99
10	0.81	0.92	0.608	0.821	25.40	0.67	0.94	0.662	0.741	27.04

For partial series estimates, catchment area explained between 66% (T = 10 years) and 75% (T = 1.1 years) of the variation in discharge (Table 4.2), with R^2 values decreasing as average recurrence intervals increased. Baseflow (a) ranged from 0.34 to 0.67 m^3s^{-1}, and increased as average recurrence interval increased, while the scaling factor b ranged from 0.89 to 0.94 (mean = 0.91) (Figures 4.3a and 4.3b respectively). RSE values ranged from 0.57 to 0.74. The value of both the power-law coefficient a and the power-law exponent b was larger for partial series estimates than annual series estimates at all values of T, while R^2 values were higher for annual series estimates than partial series estimates at all values of T except T = 10 years. RSE was lower for annual series than partial series at all values of T except T = 1.1 and T = 10 years. Plots of the relationship between flood discharge and catchment area for north-eastern Tasmanian streamflow stations using both annual and partial series flood frequency estimates are provided in Figures 4.2a and 4.2b, with the lines on each plot representing the least squares linear regression of the log transformed variables.

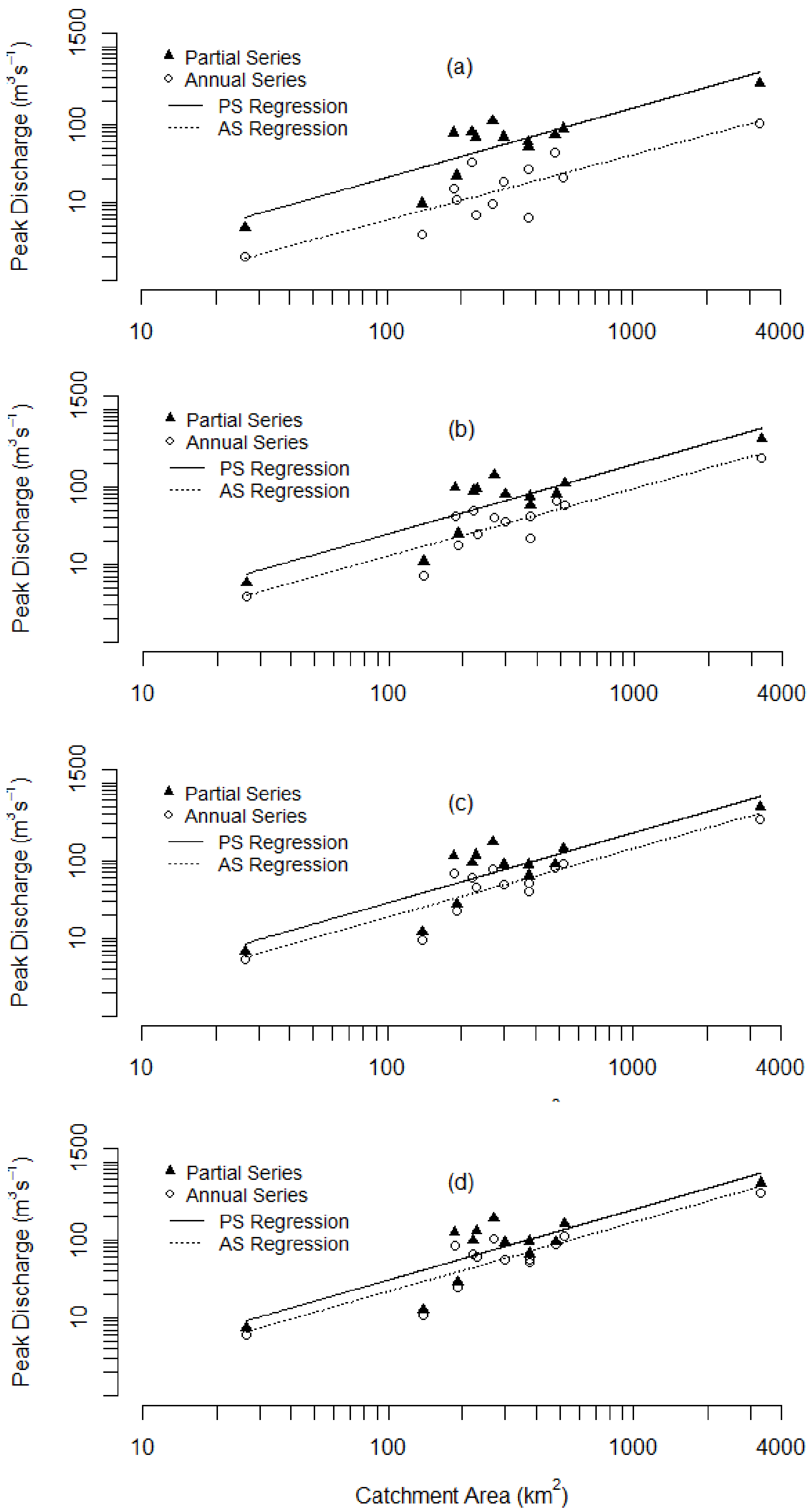


Figure 4.2a. Relationship of flood discharge to catchment area for north-eastern Tasmanian streamflow stations using both annual and partial series flood frequency estimates for T = (a) 1.1, (b) 1.5, (c) 2 and (d) 2.33 years. Lines represent least squares linear regression of log transformed variables.

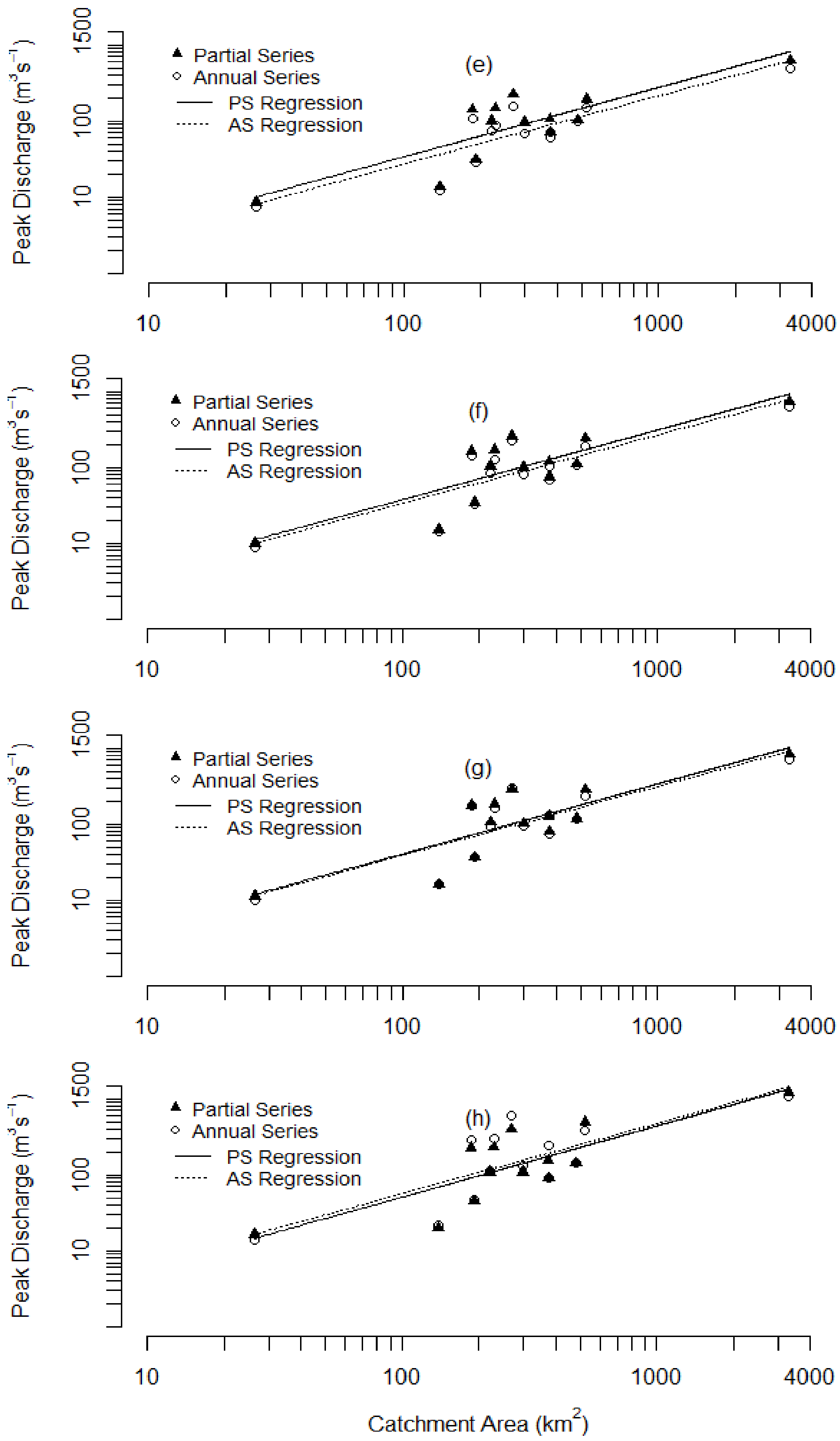


Figure 4.1b. Relationship of flood discharge to catchment area for north-eastern Tasmanian streamflow stations using both annual and partial series flood frequency estimates for T = (e) 3, (f) 4, (g) 5, and (h) 10 years. Lines represent least squares linear regression of log transformed variables.

A further analysis was undertaken to test the influence of individual observations on the regional relationships. The large differences in catchment area (the explanatory variable) that exist between sites can help improve precision of regression estimates, especially in consideration of the limited sample size of streamflow stations available for this analysis. Increasing the separation between values reduces the estimated variance of the slope estimate and reduces the standard error of points on the fitted line (Maindonald and Braun, 2010). However regression coefficients are very sensitive to the presence of extreme values as these tend to have extremely large residuals (Griffith et al., 1991). Consequently particular attention was paid to the two sites at the lower and upper extremes of catchment area. Site 12 (South Esk River below Macquarie River) has a catchment area almost an order of magnitude greater than any other site, while Site 10 (Ransom River at Sweet Hills) has a catchment area almost an order of magnitude smaller than other sites (Table 4.1). In addition to the leverage and Cook's distance plots mentioned previously, a jackknife analysis was undertaken on each regression to determine the influence of individual sites on the overall regression. Jackknifing is a re-sampling method which involves leaving out one observation at a time and undertaking a separate regression undertaken on each subsample, and was undertaken in this study using the 'boot" function in R with 999 replicates. The results of these analyses suggested that the general relationship holds true with subsets of the original data, as shown in a typical example in Figure 4.3. To further illustrate the limited impact of these sites at the extremes of catchment area on the overall relationship, regression models with these sites excluded were also developed. Figure 4.4 shows the power-law relationship between catchment area and partial series estimates of discharge at T = 2.33 years, with lines representing the regression with and without catchment area outliers shown.

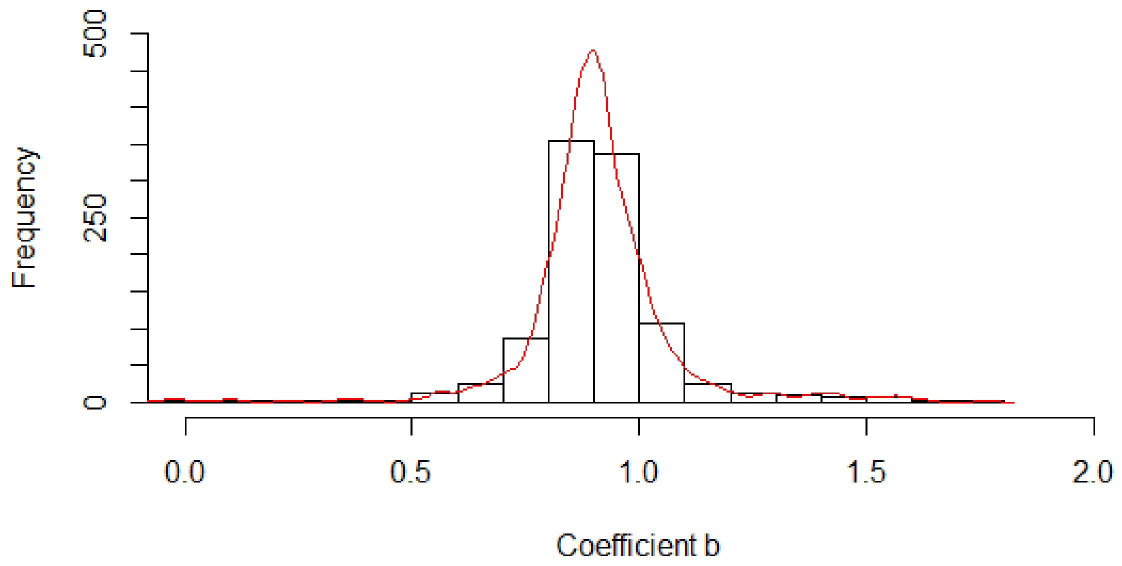


Figure 4.3. Frequency of power-law coefficient *b* estimates using jackknife bootstrapping (999 replicates) of the linear regression between log catchment area and log discharge at T = 2.33 years using partial series estimates. A density line is fitted to the histogram.

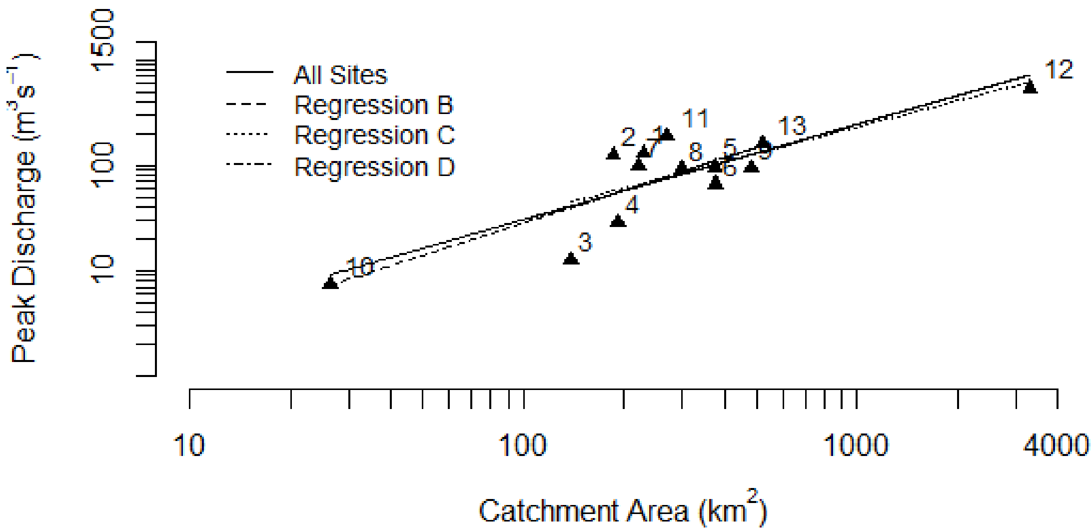


Figure 4.4. Power law relationship between discharge and catchment area for T=2.33 years using partial series data from all sites (All Sites, n =13), with site 12 removed (Regression B, n =12), with site 10 removed (Regression C, n =12) and with both site 12 and site 10 removed (Regression D, n =11).

Plots of the power-law coefficient and exponent a and b against average recurrence interval T for both partial and annual series discharge estimates are provided in Figure 4.5. Values of the coefficient a estimated using the partial series datasets were significantly smaller than estimates using annual series data at low average recurrence intervals (T = 1.1 years) but the two values merged at around T = 2.33 years. The largest difference between annual series and partial series estimates of exponent b occurred at T = 1.1 years (0.05) and reduced to around 0.14 by T = 2.33 years, and this difference was maintained through to T = 10 years.

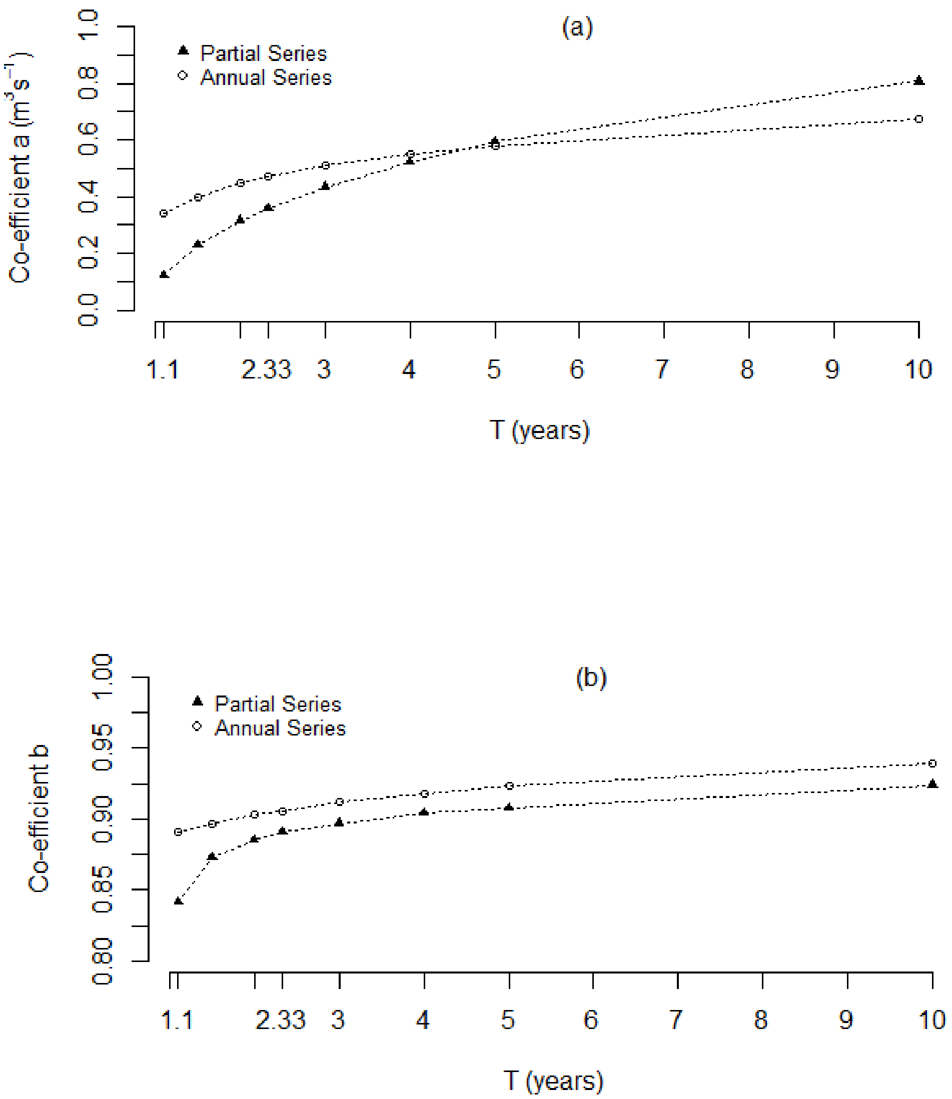


Figure 4.5. Coefficients for the discharge-catchment area power-law relationship using both annual and partial series magnitude-frequency estimates. (a) power-law coefficient a; and (b) power-law exponent b. T = average recurrence interval in years.

Analysis of covariance showed there was no significant difference between exponent b in the linear regression between log discharge and log catchment area, estimated using flood frequency data based on the annual series and estimates based on partial series data (the slope of the regression line) at any recurrence interval (Table 4.3). However, there was a significant difference in coefficient a (the log of the intercept of the regression line) at T = 1.1, 1.5 and 2 years (f = 34.24, p < 0.001 at T = 1.1 years; f = 11.16, p < 0.005 at T = 1.5 years and f = 34.24, p = 0.05 at T = 2 years. The significance levels in Table 4.3 should however be interpreted with caution as the correlation between annual and partial series flood frequency estimates means the data are not statistically independent. However, the significance levels for a difference between annual series and partial series log intercepts (a) is large at T = 1.1 and T = 1.5 years.

Table 4.3. Analysis of Covariance (ANCOVA) results investigating differences in the relationship between discharge and catchment area using annual and partial series flood frequency estimates. 1. The influence of annual or partial flood frequency estimates on exponent b (H_0: $b_1 = b_2$) via ANCOVA with interaction; and 2. The influence of annual or partial flood frequency estimates on the log of coefficient a via ANCOVA without interaction (H_0: $a_1 = a_2$). (ns = no significance).

***T* (years)**	**1. Interaction**		**2. No interaction**	
	***f*-value**	***p***	***f*-value**	***p***
1.1	0.05	ns	34.24	< 0.001
1.5	0.01	ns	11.16	< 0.005
2	0.01	ns	4.30	0.050
2.33	0.01	ns	2.55	ns
3	0.00	ns	1.02	ns
4	0.00	ns	0.29	ns
5	0.00	ns	0.06	ns
10	0.00	ns	0.10	ns

4.4. Discussion

4.4.1. Comparison of annual and partial series relationships

Little difference was found between the discharge-catchment area relationships produced using annual series flood frequency estimates and those based on partial series estimates (Table 4.3 and Figure 4.2). However log(a) determined using flood frequency estimates based on annual series data was significantly less than log(a) determined using partial series data at the lowest average recurrence intervals (T = 1.1, 1.5 and 2 years) (Table 4.3). There was also a strong trend across other average recurrence intervals for both the coefficient and the exponent of the power-law relationship developed using annual series flood frequency estimates to be smaller, although not significantly so, than that developed using partial series estimates, with the difference largest at the lowest average recurrence interval and decreasing as average recurrence interval increased (Table 4.2 and Figure 4.2).

The larger values of the coefficient a obtained from partial series estimates in comparison to those from annual series estimates at low average recurrence intervals (Table 4.2 and Figure 4.2a, 4.2b and 4.2c) can be explained by the larger magnitude flood frequency estimates of small floods provided by the partial series (Appendix 4.2). The coefficient a indicates the flow at a unit area, and if discharge increases while the unit area remains the same, a will increase. The trend for the difference in a between the two series to decrease as T increases (Figure 4.5a) may be explained by the differences in flood frequency estimates between the annual and partial series decreasing as T increases, with annual series flood frequency estimates becoming roughly equivalent to partial series estimates at around $T = 5$ years, and becoming larger than partial series values at $T = 10$ years (Appendix 4.2). Figure 4.5.a also illustrates the larger range of values in coefficient a determined using the partial series in comparison to annual series.

The relationship between values of the power-law exponent b obtained from annual series estimates and those from partial series estimates was quite different to that of the coefficient a (Figure 4.5.b). Annual series estimates of the power-law exponent b were smaller than partial series estimates across all values of T, and the range of annual series values of b (0.09) over the range of T examined was smaller than that of partial series values (0.05).

The power-law coefficient (a) and the power-law exponent (b) determined using both annual and partial series flood frequency estimates became progressively larger with increasing average recurrence interval. The increase in the values of the power-law coefficient a as T increases (Table 4.2) is expected given that increases in T results in progressively larger flood discharges and coefficient a indicates the flow at a unit area. Knighton (1987) suggested that b ordinarily decreases as T increases because greater channel and valley storage attenuate the flood wave at higher flows. He suggested that the reverse occurred in north-eastern Tasmanian streams due to the low levels of storage available so that translation rather than reservoir effects dominate the downstream transmission of flood. The increase in b as T increased in this study mirrors the results of Knighton (1987).

The stronger relationships (larger R^2 values) between discharge and catchment area using annual series flood frequency values in comparison to those using partial series estimates suggests that it may be better described by the linear relationship between the log transformed variables than the partial series relationship. This is supported by the lower *RSE* values for annual series estimates in comparison to partial series estimates (Table 4.2). Conversely, the relationship between discharge and catchment area using partial series flood frequency values may be better described by a non-linear relationship between the variables. This is supported by the fits of the log transformed data series to the normal distribution (Appendix 4.3). However it should be remembered that in practice, few empirical phenomena obey power laws across the full range of values (Clauset et al., 2009), and while examination of the error distribution of the different relationships would provide further insight into models that could better describe the relationship (Xiao et al., 2011), that was not the purpose of this study.

A large range of catchment areas was used in this study (largest site > 100 times the catchment area of the smallest site) (Table 4.1) in an attempt to reduce the estimated variance of the slope estimate and reduce the standard error of points on the fitted line (Maindonald and Braun, 2010), as well as to ensure the developed relationships are valid over an extended range. However as extreme values tend to have extremely large residuals (Griffith et al., 1991), a number of techniques was used to assess the influence of the smallest and largest catchment areas on the values of exponent *b*. In addition to normal regression diagnostic tools (leverage and Cook's distance plots), both jackknife resampling (Figure 4.3) and plots of the regression lines (Figure 4.4) were used, with all assessments indicating that the relationships developed were not unduly influenced by the presence of these catchment area outliers.

It is interesting to note the difference in behaviour of the plotted regression lines of both annual series and partial series estimates of the coefficient *a* and the exponent *b* as they approach the origin (Figure 4.5). The partial series provides intuitively better results as discharge approaches 0 as average recurrence interval approaches 0. Overall, while the discharge-catchment area relationships produced using annual series flood frequency estimates were similar to those based on partial series estimates, the results of this study suggest that partial series relationships will provide better estimates of the power-law coefficient and exponent at low average recurrence intervals ($T \leq 2$ years).

4.4.2. Comparison of results from this study with those from other studies

The relatively strong relationships found between discharge and catchment area in this study across all average recurrence intervals and using both annual and partial series flood frequency estimates (Table 4.2) reflect the strong relationships previously found in this region. In a study using data from north-eastern Tasmanian streamflow data, Knighton (1987) found that more than 97% of the variation in flood discharges was explained by catchment area. The weaker association found in this study (61 – 82% for annual series flood frequency estimates) may be explained by a number of factors. Firstly, this study used a dataset which was larger and with a wider range of catchment areas than those used by Knighton. Secondly, changes in the strength of the relationship may be a result of the different flood frequency estimation techniques that were used in the two studies. Finally, the hydrology of the region is likely to have altered due to a changed climate, with an estimated 12% reduction in mean annual rainfall occurring in the Pipers-Ringarooma region of north-eastern Tasmania in the period 1997 to 2007, relative to historical climate (1924 to 2007) (CSIRO, 2009).

The values of the power-law relationship coefficient *a* and exponent *b* from this study (Figure 4.5) fall within the range of values found in other studies (Table 4.4), both globally and in Australia. However the comparison of regional regression coefficients between different studies is problematic and should be undertaken with caution. Data quantity, quality and type, flood frequency estimation techniques and regression methods vary between studies, and there is frequently a lack of detail on which methods have been employed. In addition, difficulties exist in comparing values of *a* across different studies due to the use of different units (Galster, 2007). However, if these limitations are acknowledged, comparison of the results from different regions is valid.

Table 4.4. Selected summary of coefficients and exponents for discharge-catchment area relationships for small floods following the general form of $Q_T = aA_d^{b,}$ where Q_T = discharge with an average recurrence interval of T years, A_d = discharge, a is the power-law coefficient representing base discharge (m^3s^{-1}) and b is a scaling exponent (n = number of stations, bf = bankfull discharge).

Source	**Location**	***n***	***T***	***a***	***b***
(Leopold et al., 1964)	US				0.65-0.8
McKerchar and Pearson (1989) quoted in (McKerchar and Pearson, 1990)	New Zealand		2.33[a]		0.8
(Leclerc and Lapointe, 1994)	Southern Quebec	26	2.33 [a]	0.03	0.96
			bf	1.64	0.71
(Galster, 2007)	US		2.33[a]		0.49-0.97
(Stacey and Rutherford, 2007)	Virginia, USA	9	1.5	0.56[b]	0.80
(Rachol and Boley-Morse, 2009)	Michigan, USA	43	2	4.05 [b]	0.95
Australia					
(Alexander, 1972)	Australia				0.7
(Gippel, 1985)	Hunter Valley, NSW	36	bf	1.51	0.91
(Loebis, 2002)	Australia	6	2.33 [a]	1.58	0.81
(Reinfelds et al., 2004)	Bellinger, NSW		2	0.89	0.80
(Worthy, 2005)	Cotter River, ACT		2	0.12	0.98
(Jain et al., 2006)	Upper Hunter, NSW	19	2	1.21	0.72
Tasmania					
Watson (1975) quoted in (Knighton, 1987)	Western Tasmania	7	2	4.70 [b]	0.74
Watson and Williams (1983) quoted in (Knighton, 1987)	Western Tasmania	10	2	5.19 [b]	0.75
(Hughes, 1987)	Tasmania	77	2.33 [a]	0.88	0.87
(Knighton, 1987)	North-eastern Tasmania	9	1.11	0.23	0.84
			2	0.32	0.93
			5	0.40	0.98
			10	0.45	1.01
This study	North-eastern Tasmania	13	1.1	0.34	0.89
			1.5[C]	0.40	0.90
			2 [C]	0.45	0.90
			2.33 [C]	0.47	0.91
			3 [C]	0.51	0.91
			5 [C]	0.58	0.92
			10 [C]	0.67	0.94

([a] Results are for mean annual flood, which is generally thought to be equivalent to T = 2.33 years (Knighton, 1999); [b] results are in miles; [c] results are from partial series flood frequency estimates)

While common values of the coefficients from Equation 4.1 are around 1 for *a* and 0·7 for *b* (Dunne and Leopold, 1978, Jain et al., 2006, Pérez-Peña et al., 2009), a relatively large range of values have been found worldwide (Table 4.4). Values of partial series coefficient *b* from this study were larger than those found in the US (Leopold et al., 1964, Stacey and Rutherford, 2007) (Table 4.4), and slightly less than those found in Quebec (Leclerc and Lapointe, 1994), which is at a similar latitude to the sites in this study. Where the scaling factor $b = 1$, the relationship between catchment area and discharge is linear. Linear scaling occurs in basins with uniform hydrology, including precipitation and runoff; although the scaling may depend on the exact discharge (*T*) chosen for the analysis. When $b < 1$ than less discharge is being added by the downstream catchment area than the upstream area (Galster, 2007). In a study of the relationship between mean annual flow (commonly considered to be $T = 2.33$ years) and catchment area using weighted least squares regression and data from more than a thousand global rivers, McMahon et al. (2007), found Australian and South African streams had values of $a = 1.013$ and $b = 0.727$, while streams from the rest of the world had values of 1.526 and 0.818 for *a* and *b* respectively. These results are not necessarily reflected in the selected data in Table 4.4 where values for *b* for Australian studies ranged from 0.81 to 0.91 at $T = 2.33$ years, compared to a range of 0.49 to 0.96 for studies from the rest of the world. This study has low values of *a* and high values of *b* in comparison to those derived from the amalgamated Australian and South African data set of McMahon et al. (2007), and the same pattern exists between the results of this study and the other Australian studies shown in Table 4.4.

There may be a number of explanations of these results. Galster (2007) suggested that in larger catchments the time taken for water to travel to the mouth of a watershed complicates the scaling of discharge with catchment area. River regulation and water usage is generally higher in the lower parts of catchments, particularly in Australia where human settlements are clustered along the coast. Australian rivers may have lower values of *b* then those from other parts of the world as a result of these lower parts of the catchments contributing less discharge than upper catchment areas which are often much less impacted. North-eastern Tasmanian rivers are largely unregulated, and human habitation and water usage is higher in inland areas away from the coast. This may result in more discharge being added in downstream catchment areas in north-eastern Tasmania then elsewhere and account, at least in part, for the high *b* values. Galster (2007) suggested smaller catchments, particularly those that are undisturbed, have *c* values near 1 as a result of the short time required for discharge to travel through the catchment.

This study from north-eastern Tasmanian catchments found higher values of exponent *b* relative to those using data from western Tasmania (Table 4.4), which may be expected as these two regions experience differences in rainfall, topography and geology. The results from this study suggest that discharge in north-eastern Tasmanian rivers has a much more linear relationship with catchment area than western Tasmanian rivers, which may be expected as western Tasmanian rivers rise on the slopes of the west coast ranges and generally travel only a short distance to the west coast to discharge. Western Tasmania also generally experiences higher frequency and longer duration storms than eastern Tasmania (McConachy et al., 2003), largely concentrated in upper catchment areas. The values of exponent *b* at T = 2.33 years using annual series flood frequency estimates in this study was similar to that found by Hughes (1987), who used annual series data from 77 Tasmanian streamflow stations to undertake hydrological analyses. The value of coefficient *a* in this study was lower than that found by Hughes, but as Hughes included sites located across Tasmania differences are expected. Using annual series data from north-eastern Tasmania, Knighton (1987) found a range of values of coefficients in the discharge-catchment area power law relationship similar to those found in this study. The values of coefficient *a* from this study estimated using annual series flood frequency estimates were lower than those found by Knighton at T = 1.1 years, but were equivalent at T = 2 years. The values of coefficient *a* from this study at T = 5 years and T = 10 years were progressively larger than those found by Knighton. The values of coefficient *b* found in this study was equal to that found by Knighton at T = 1.1 years, but were progressively smaller at T = 2, 5 and 10 years. While these differences may reflect actual temporal changes in precipitation, it is equally possible they reflect the different datasets and techniques used. Knighton used a smaller dataset than this study, which is likely to increase both the statistical error on the scaling parameter and the bias from finite size effects (Clauset et al., 2009). Catchment area (A_d) values used in this study may also be significantly different to those used by Knighton, due to the different methods used.

4.4.3. Intra-regional variation in the power-law relationship

Fluctuations around the regional relationship between discharge and catchment area can identify inter-basin contrasts in flood generation and transmission (Knighton, 1987). In this study there was a similar scatter of sites to those of Knighton around the regional regression line relating discharge to catchment area for both annual and partial series flood frequency estimates across all values of T. The distribution of sites about the regression line for partial series estimates of discharge at T = 2 years (Figure 4.6) is typical. The Ansons (1), Break

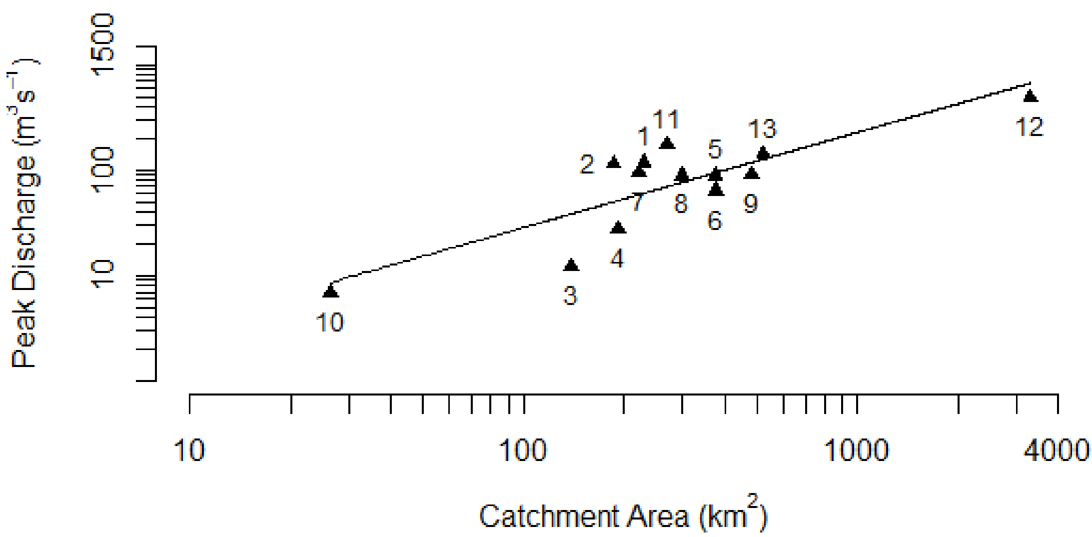


Figure 4.6. The distribution of individual sites around the line representing the power law relationship between discharge and catchment area using partial series flood frequency estimates for $T = 2$ years. Names for each site are provided in Table 4.1.

O'Day (2), Nile (7) and Scamander (11) River sites (Table 4.1) generally plotted as positive residuals, while the Brid (3), Great Forester (4) and North Esk (6) sites plotted as negative residuals. The first group are mostly on the east coast and the second group (apart from the North Esk) are on the north coast (Figure 4.1), suggesting the difference may reflect an environmental control. North-eastern Tasmanian rivers which discharge to the north coast have been characterized as low variability (LV) rivers, having generally higher and more consistent baseflows, no cease-to-flow periods, and a lower magnitude of difference between high flow events and mean flows. In contrast, high variability (HV) sites have a larger range of flow conditions, with more variable baseflows, and large floods, often of very high magnitudes compared to their average baseflows (DPIPWE, 2010). The other river which discharges to the north coast is the Pipers River, which plots close to the regression line. Unfortunately, a full hydrological categorisation of north-eastern Tasmanian catchments using the HV/LV methodology has not been undertaken, so the validity of this relationship between negative residual on regional and LV rivers cannot be further investigated. The spread of sites around the regression line is not dissimilar to that of Knighton (1987), who found the upper South Esk River plotted as a positive residual and the Brid, North Esk and lower South Esk Rivers plotted as negative residuals. The current South Esk River site (12) is much lower in the catchment than Knighton's upper South Esk River site, but also plots slightly below the regression line at some values of T (Figure 4.6). Knighton suggested that the Pipers River may be regarded as typical of north-eastern Tasmanian rivers as it showed very little deviation from the regional regression lines, and this also proved be the case in this study, where the Pipers River (8) plotted very close to the regression line (Figure 4.6). More generally, Knighton suggested that north-eastern Tasmanian rivers draining wetter catchments had positive residuals, while the rivers draining drier catchments plotted as negative residuals (Knighton, 1987). The results of this study also show some agreement with the grouping of Tasmanian rivers suggested by Hughes (1987), who divided streamflow stations in the north-eastern region into two groups, with one group containing stations on the Brid, North Esk and Ringarooma Rivers and the other containing a station on the Pipers River, amongst other sites. While all regions will experience some fluctuation in the discharge catchment area relationship because of spatial non-uniformity in substrate and temporal unsteadiness in precipitation and soil moisture (Galster, 2007), the residual scatter of sites around a regional relationship may also be a result of variability in flood storage or drainage network organisation (Leclerc and Lapointe, 1994). Bates (1994) suggests that the location of the gauged site within a catchment is important. In larger watersheds the travel time of water from the upper catchment to the mouth of a watershed complicates the scaling of discharge with catchment area (values of b) (Galster, 2007).

4.4.4. Limitation of this study

There are a number of factors which introduce error and uncertainty into the results of this analysis. The use of linear regression of log-transformed parameters to interpret the power law relationship is common practice, and the results of studies using this method have been found to be generally valid (Xiao et al., 2011). However other studies have expressed concerns about this method (Clauset et al., 2009), and another study has shown that log-transformation may introduce a systematic bias into power-law calculations because the largest values are compressed on the logarithmic scale (Hui and Jackson, 2007).

Sampling error also introduces uncertainty to the results. The number (the sample size) of streamflow stations will also impact on the accuracy of the results, as well as the ability to correctly determine significant differences in the results. Stewardson et al. (2005) found the exponents in the at-a-station power law relationship between discharge and width were quite sensitive to sample size, and in an allometric study using the power law relationship, Hui (2007) found that the probability of both rejecting a true null hypothesis and accepting the false null hypothesis was strongly increased by small sample sizes. The range of streamflow stations included, as *a* and *b* are very sensitive to the presence of extreme values as these tend to have extremely large residuals (Galster, 2007)

Measurement error can also affect the results. While catchment area estimates have been found to be reasonably accurate (Lima and Lall, 2010), there is a large degree of uncertainty around flood frequency estimates, which can be impacted by the length and quality of the streamflow record as well as the method of analysis. The shorter the record length, the lower the expected accuracy of flood estimates, and a lack of homogeneity in the record due to changes such as altered landuse, abstraction and regulation will also reduce flood the accuracy of flood frequency estimates.

In addition to the above limitations, it has been suggested that the power law method is not suited to areas larger than medium scale catchments, as the interplay between groundwater, evaporation, climatic zones and discharge may introduce errors beyond meaningful limits (Finlayson & Montgomery, 2003; quoted in Worthy, 2005). Despite these limitations, the study fulfills its aim of producing first order estimates of discharge for north-eastern Tasmanian rivers and streams, and comparisons with other studies are generally valid as they face similar limitations.

4.5. Conclusion

This study developed regional discharge-catchment area power-law relationships using data from north-eastern Tasmanian streamflow stations. The relationships developed using flood frequency estimates based on annual series data were also compared with those based on partial series data sets. This study made several findings:

1. There is a strong relationship between peak discharge and catchment area for small magnitude floods ($T \leq 10$ years) in north-eastern Tasmania based on regional power-law relationships.

2. There was no significant difference between the power-law coefficient and exponent of the discharge-catchment area relationships produced using annual series flood frequency estimates and those based on partial series estimates other than for log(a) at the low average recurrence intervals (T = 1.1, 1.5 and 2 years). However there was a strong trend for both the coefficient and the exponent of the power-law relationship developed using annual series flood frequency estimates to be smaller than those developed using partial series estimates, with the difference largest at the lowest average recurrence interval and decreasing as average recurrence interval increased.

3. Values for the exponent b in the power-law relationship were generally closely clustered in the range of 0.89 to 0.92, irrespective of the value of T or whether the annual series or partial series data set was used for flood frequency estimates. The results of this study, supported by those of other studies, suggest that the power-law relationship between discharge and catchment area is a suitable method for making first-order estimates of peak discharge at ungauged sites in north-eastern Tasmania and that 0.90 is a reasonable value for the exponent b in the equation that expresses the relationship.

4. Values of the regression exponent b found in this study were generally higher than those found elsewhere in Australia or globally, but were in a similar range to those found in a previous study of north-eastern Tasmania.

5. Within the north-eastern Tasmanian region, the Ansons (1), Break O'Day (2), Nile (7) and Scamander (11) River sites generally plotted above the regional curve, while the Brid (3) and Great Forester (4) and North Esk (6) River sites plotted as negative. These negative residual sites belong to a group characterized as being of low hydrological variability.

Appendix 4.1. Peaks-over-threshold details

Peaks-over-threshold (POT) details for the development of partial series data sets used in flood frequency estimates to develop regional regressions between discharge and catchment area. A minimum of 14 days was set between flood events, k = number of flood events included in data set, threshold Q = discharge level below which flood peaks are discarded and n = number of years of stream flow record).

Site number	k	Threshold Q (m^3s^{-1})	k/n
1	15	25.00	1.5
2	56	30.00	2.0
3	68	6.80	2.0
4	82	15.90	2.0
5	64	19.00	2.0
6	170	36.20	2.0
7	20	40.87	2.0
8	59	41.00	1.5
9	68	56.50	2.0
10	70	2.40	2.5
11	25	22.00	2.5
12	138	146.00	2.5
13	58	38.80	2.5

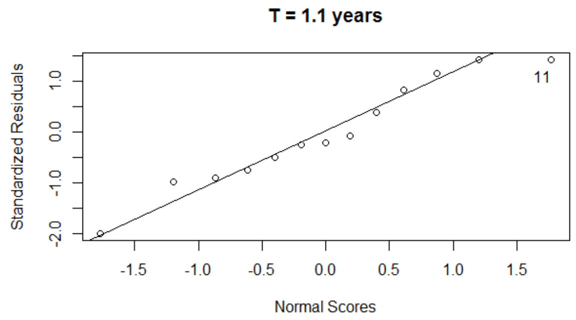
Appendix 4.1. Flood frequency estimates

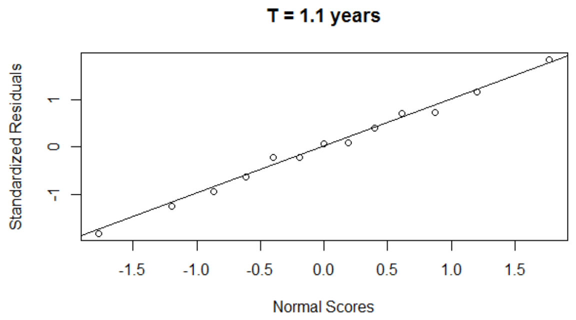
Flood frequency estimates for 13 north-eastern Tasmanian streamflow stations using the partial and annual series datasets.

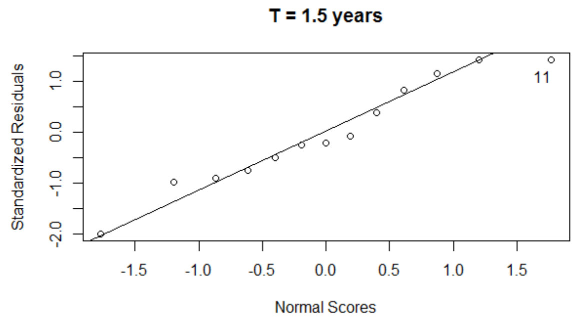
Site	Partial series flood frequency estimates m^3s^{-1}								Annual series flood frequency estimates m^3s^{-1}							
	Average Recurrence Interval (years)								Average Recurrence Interval (years)							
	1.1	1.5	2	2.33	3	4	5	10	1.1	1.5	2	2.33	3	4	5	10
1	68.35	93.94	116.84	128.68	147.82	168.91	184.78	231.47	6.91	24.58	46.13	60.62	88.43	126.75	162.09	295.78
2	78.43	98.04	116.52	126.45	143.06	162.24	177.31	225.31	15.08	42.56	68.36	82.80	109.63	144.07	173.05	284.42
3	9.60	10.80	11.97	12.61	13.71	15.02	16.08	19.63	3.83	7.09	9.37	10.58	12.43	14.52	16.24	21.51
4	21.93	24.57	27.18	28.63	31.13	34.13	36.58	44.94	10.69	17.54	22.55	24.75	28.66	32.92	36.31	46.81
5	60.17	75.21	88.62	95.52	106.65	118.87	128.03	154.79	6.29	22.14	40.63	51.65	72.77	104.15	133.52	245.30
6	51.96	57.80	63.05	65.77	70.17	75.04	78.71	89.56	26.88	41.31	50.70	54.83	61.73	69.38	75.10	92.67
7	79.16	87.85	93.88	96.46	99.98	103.07	104.94	108.73	33.07	50.23	61.66	67.12	75.58	84.45	91.88	112.09
8	68.55	80.01	87.98	91.39	96.03	100.11	102.58	107.59	18.62	35.77	49.35	56.51	68.26	82.02	93.52	130.25
9	73.87	81.57	89.19	93.44	100.79	109.66	116.93	141.94	42.75	65.36	79.75	86.78	97.82	109.49	118.15	146.59
10	4.70	5.67	6.72	7.34	8.47	9.95	11.25	16.35	1.98	3.87	5.39	6.14	7.42	8.92	10.03	13.96
11	109.46	140.84	172.12	189.64	220.08	257.07	287.58	393.55	9.36	39.68	77.51	104.67	154.44	222.70	295.45	609.39
12	331.01	407.71	489.56	537.71	625.39	738.71	837.77	1220.79	102.42	233.00	343.81	403.93	502.76	620.90	710.99	1058.73
13	87.45	111.78	140.21	158.08	192.72	241.36	287.30	493.01	20.89	57.65	92.66	112.48	148.73	193.58	234.14	383.67

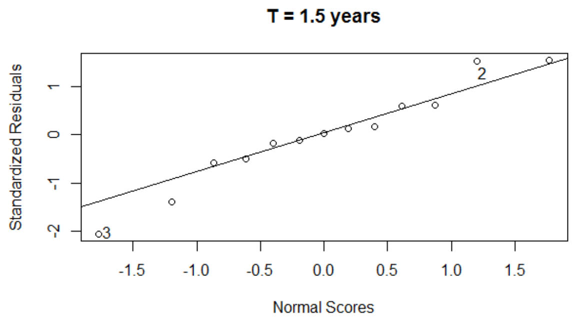
Appendix 4. 2. Normal probability plots

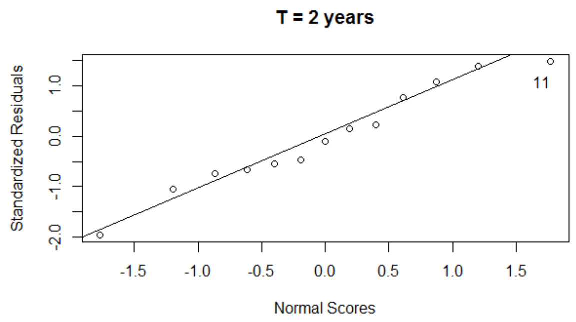
Normal probability plots for the linear regression of the log transformed parameters of discharge and catchment area from north-eastern Tasmanian streamflow stations for average recurrence intervals (T) = 1, 1.1, 2, 2.33, 3, 4, 5, and 10 years using annual series (right) and partial series (left) flood frequency estimates. The distribution of points around the line represents the distribution of the error around the normal distribution.

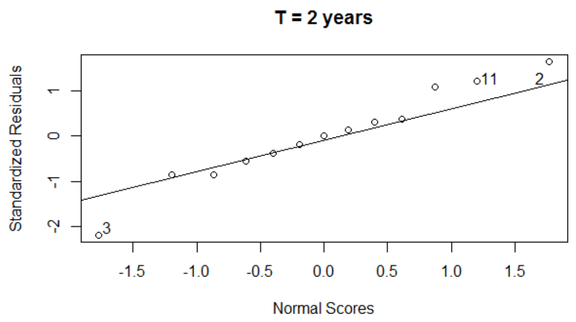


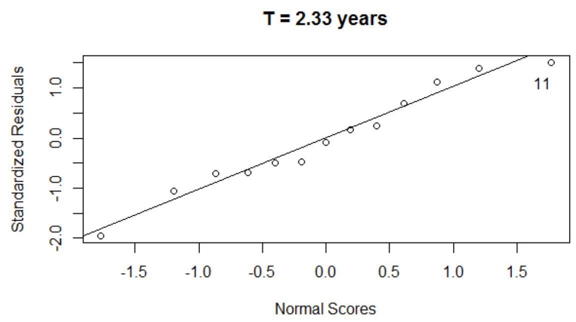


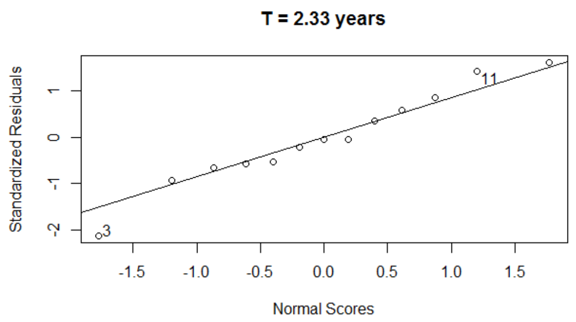


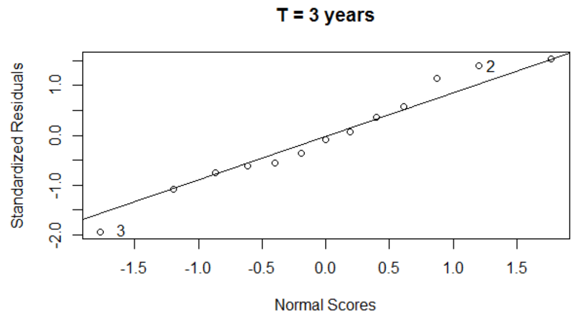


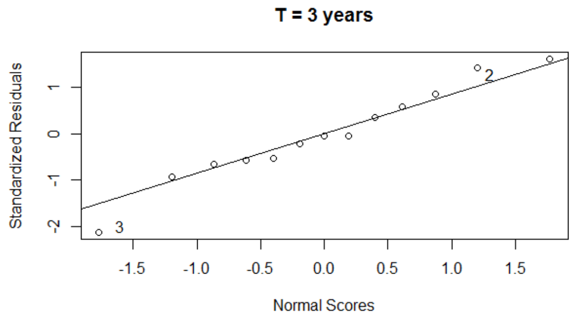


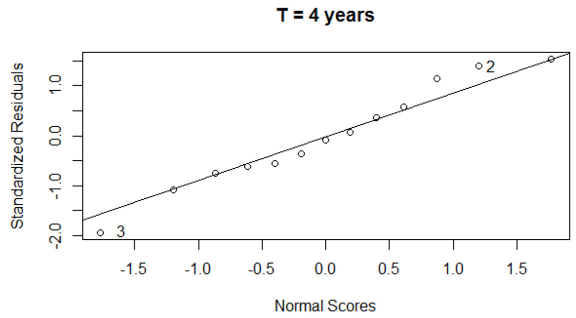







T = 3 years
Standardized Residuals
Normal Scores
3
2


T = 3 years
Standardized Residuals
Normal Scores
3
2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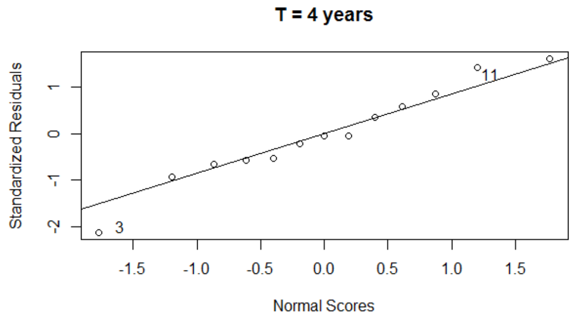
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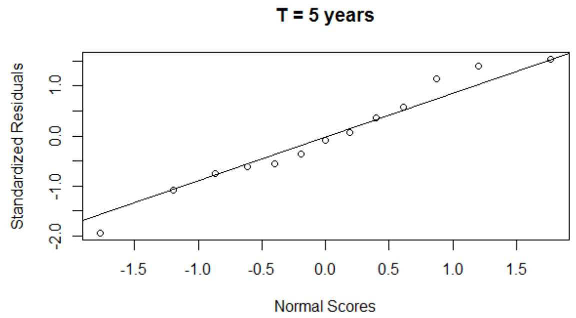
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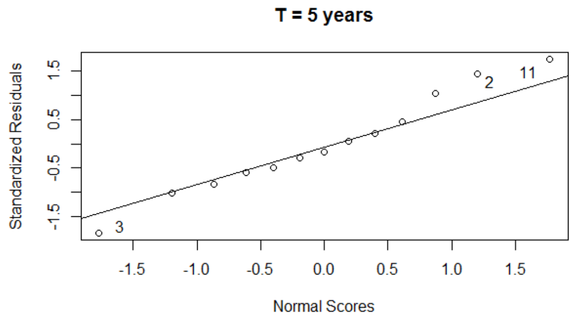
Normal Scores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Normal Scores
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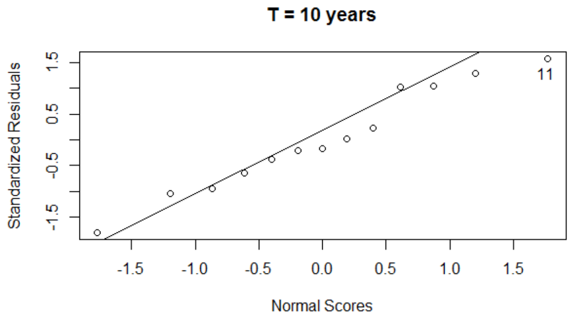
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Standardized Residuals
Normal Scores
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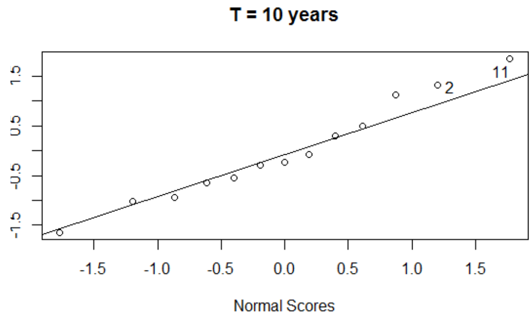

T = 10 years
Normal Scores
2
11

References

ADAMOWSKI, K., LIANG, G.-C. & PATRY, G. G. 1998. Annual maxima and partial duration flood series analysis by parametric and non-parametric methods. *Hydrological Processes*, 12**,** 1685-1699.

ALEXANDER, G. N. 1972. Effect of catchment area on flood magnitude. *Journal of Hydrology*, 16**,** 225-240.

ARMSTRONG, W. H., COLLINS, M. J. & SNYDER, N. P. 2012. Increased Frequency of Low-Magnitude Floods in New England. *Journal of the American Water Resources Association*, 48**,** 306.

BATES, B. C. 1994. *Regionalisation of Hydrologic Data: A Review: a Report as Part of Project D2: Regionalisation and Scaling of Hydrologic Data*, CRC for Catchment Hydrology, Department of Civil Engineering, Monash University.

BUREAU OF METEOROLOGY 1993. *Climate of Tasmania,* Canberra, ACT, Australian Government Pub. Service.

CLAUSET, A., SHALIZI, C. R. & NEWMAN, M. E. J. 2009. Power-law distributions in empirical data. *SIAM Review,* 51**,** 661-703.

CSIRO 2009. Water availability for the Pipers-Ringarooma region. *Tasmania Sustainable Yields Project.* Australia: CSIRO

CUNNANE, C. 1978. Unbiased plotting positions — A review. *Journal of Hydrology,* 37**,** 205-222.

DPIPWE 2005. Conservation of Freshwater Ecosystem Values Project (CFEV) database. Tasmania: Water and Marine Resources Division, Department of Primary Industries, Parks, Water and Environment.

DPIW 2008. Conservation of Freshwater Ecosystem Values (CFEV) Project Technical Report. Hobart, Tasmania: Conservation of Freshwater Ecosystem Values Program, Department of Primary Industries and Water.

DUNNE, T. & LEOPOLD, L. B. 1978. *Water in environmental planning,* San Francisco, W.H. Freeman and Company.

FOX-HUGHES, P. 2009. A heavy rainfall event in Northern Tasmania during 27 to 30 January 2004. *Australian Meteorological and Oceanographic Journal* 58**,** 151-166.

GALSTER, J. C. 2007. Natural and anthropogenic influences on the scaling of discharge with drainage area for multiple watersheds. *Geosphere,* 3**,** 260-271.

GIPPEL, C. 1985. Changes in stream channel morphology at tributary junctions, Lower Hunter Valley, New South Wales. *Australian Geographical Studies*, 23**,** 291-307.

GRIFFITH, D. A., AMRHEIN, C. G. & DESLOGES, J. R. 1991. *Statistical analysis for geographers,* New Jersey, Prentice Hall Englewood Cliffs.

GUPTA, V. K. & DAWDY, D. R. 1995. Physical interpretations of regional variations in the scaling exponents of flood quantiles. *Hydrological Processes*, 9**,** 347-361.

HADDAD, K. & RAHMAN, A. 2011. Selection of the best fit flood frequency distribution and parameter estimation procedure: A case study for Tasmania in Australia. *Stochastic Environmental Research and Risk Assessment,* 25**,** 415-428.

HADDAD, K., RAHMAN, A., LING, F. & WEINMANN, E. Towards a New Regional Flood Frequency Analysis Method for Tasmania. *In:* VALENTINE, E. E. A., CJ (EDITOR); BALL, J (EDITOR); CHANSON, H (EDITOR); COX, R (EDITOR); ETTEMA, R (EDITOR); KUCZERA, G (EDITOR); LAMBERT, M (EDITOR); MELVILLE, BW (EDITOR); SARGISON, JE (EDITOR). ed. Proceedings of the 34th World Congress of the International Association for Hydro- Environment Research and Engineering: 33rd Hydrology and Water Resources Symposium and 10th Conference on Hydraulics in Water Engineering., 2011 Barton, A.C.T., 170-177.

HE, L. & WILKERSON, G. V. 2011. Improved Bankfull Channel Geometry Prediction Using Two-Year Return-Period Discharge. *Journal of the American Water Resources Association*.

HUGHES, J. M. R. 1987. Hydrological Characteristics and Classification of Tasmanian Rivers. *Australian Geographical Studies,* 25**,** 61-82.

HUI, D. & JACKSON, R. B. 2007. Uncertainty in allometric exponent estimation: A case study in scaling metabolic rate with body mass. *Journal of Theoretical Biology,* 249**,** 168-177.
INSTITUTION OF ENGINEERS AUSTRALIA 1987. Australian Rainfall and Runoff: A Guide to Flood Estimation. Canberra.
JAIN, V., PRESTON, N., FRYIRS, K. & BRIERLEY, G. 2006. Comparative assessment of three approaches for deriving stream power plots along long profiles in the upper Hunter River catchment, New South Wales, Australia. *Geomorphology,* 74**,** 297-317.
KEAST, D. & ELLISON, J. 2013. Magnitude Frequency Analysis of Small Floods Using the Annual and Partial Series. *Water,* 5**,** 1816-1829.
KNIGHTON, A. D. 1987. Streamflow characteristics of northeastern Tasmania: I. regional flood flows. *Papers & Proceedings - Royal Society of Tasmania,* 121**,** 23-33.
KNIGHTON, A. D. 1999. Downstream variation in stream power. *Geomorphology,* 29**,** 293-306.
KREIBICH, H., THIEKEN, A. H., PETROW, T., MÜLLER, M. & MERZ, B. 2005. Flood loss reduction of private households due to building precautionary measures--lessons learned from the Elbe flood in August 2002. *Natural Hazards and Earth System Science,* 5**,** 117-126.
LECLERC, R. & LAPOINTE, M. F. 1994. Hydraulic geometry of alluvial rivers in the Bois-Franks region of Southern Quabec. *Canadian Water Resources Journal,* 19**,** 237-252.
LEOPOLD, L. B., WOLMAN, G. M. & MILLER, J. P. 1964. *Fluvial Processes in Geomorphology,* San Francisco, W.H. Freeman and Co.
LIMA, C. H. R. & LALL, U. 2010. Spatial scaling in a changing climate: A hierarchical bayesian model for non-stationary multi-site annual maximum and monthly streamflow. *Journal of Hydrology,* 383**,** 307-318.
LOEBIS, J. Frequency analysis models for long hydrological time series in Southeast Asia and the Pacific region *In:* VAN LANEN, H. A. J. & DEMUTH, S., eds. FRIEND 2002: Regional Hydrology: Bridging the Gap Between Research and Practice, 2002 Cape Town, South Africa. International Association of Hydrological Sciences, 213-219.
MADSEN, H., RASMUSSEN, P. F. & ROSBJERG, D. 1997. Comparison of annual maximum series and partial duration series methods for modeling extreme hydrologic events: 1. At-site modeling. *Water Resour. Res.,* 33**,** 747-757.
MAINDONALD, J. & BRAUN, W. J. 2010. *Data analysis and graphics using R: an example-based approach,* New York, Cambridge University Press.
MALAMUD, B. D. & TURCOTTE, D. L. 2006. The applicability of power-law frequency statistics to floods. *Journal of Hydrology,* 322**,** 168-180.
MCCONACHY, F., XUEREB, K., SMYTHE, C. & GAMBLE, S. 2003. Homogeneity of Rare to Extreme Rainfalls over Tasmania. *In:* BOYD, M., BALL, J., BABISTER, M. & GREEN, J. (eds.) *28th International Hydrology and Water Resources Symposium: About Water.* Wollongong, N.S.W.: Institution of Engineers, Australia.
MCKERCHAR, A. I. & PEARSON, G. P. 1990. Maps of flood statistics for regional flood frequency analysis in New Zealand. *Hydrological Sciences Journal,* 35**,** 609-621.
MCMAHON, T. A., VOGEL, R. M., PEEL, M. C. & PEGRAM, G. G. S. 2007. Global streamflows – Part 1: Characteristics of annual streamflows. *Journal of Hydrology,* 347**,** 243-259.
MOHSSEN, M. Partial duration series in the annual domain. *In:* ANDERSSEN, R., BRADDOCK, R. & NEWHAM, L., eds. 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation, 2009 Cairns, Australia. Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation.
NANSON, G. C., PRICE, D. M., JONES, B. G., MAROULIS, J. C., COLEMAN, M., BOWMAN, H., COHEN, T. J., PIETSCH, T. J. & LARSEN, J. R. 2008. Alluvial evidence for major climate and flow regime changes during the middle and late Quaternary in eastern central Australia. *Geomorphology,* 101**,** 109-129.
PAGE, K. J. & MCELROY, L. 1981. Comparison of annual and partial duration series floods on the Murrumbidgee River. *Journal of the American Water Resources Association,* 17**,** 286-289.
PÉREZ-PEÑA, J. V., AZAÑÓN, J. M., AZOR, A., DELGADO, J. & GONZÁLEZ-LODEIRO, F. 2009. Spatial analysis of stream power using GIS: SLk anomaly maps. *Earth Surface Processes and Landforms,* 34**,** 16-25.

RACHOL, C. M. & BOLEY-MORSE, K. 2009. Estimated bankfull discharge for selected Michigan rivers and regional hydraulic geometry curves for estimating bankfull characteristics in southern Michigan rivers. *Scientific Investigations Report.* U.S. Geological Survey

RAHMAN, A., HADDAD, K., KUCZERA, G. & WEINMANN, E. 2009. Regional Flood Methods. *Australian Rainfall and Runoff.* Institution of Engineers Australia.

REINFELDS, I., COHEN, T., BATTEN, P. & BRIERLEY, G. 2004. Assessment of downstream trends in channel gradient, total and specific stream power: a GIS approach. *Geomorphology,* 60**,** 403-416.

RIBATET, M. 2011. A User's Guide to the POT Package. Version 1.4 ed.

RUSTOMJI, P. 2009. A statistical analysis of flood hydrology and bankfull discharge for the Daly River catchment, Northern Territory, Australia. *Water for a Healthy Country National Research Flagship.* Canberra, Australia: CSIRO.

STACEY, M. & RUTHERFORD, I. Testing specific stream power thresholds of channel stability with GIS. *In:* WILSON, A. L., DEHAAN, R. L., WATTS, R. J., PAGE, K., BOWMER, K. H. & CURTIS, A., eds. Proceedings of the 5th Australian Stream Management Conference, 2007 Charles Sturt University, NSW. 384-389.

STEWARDSON, M. 2005. Hydraulic geometry of stream reaches. *Journal of Hydrology,* 306**,** 97-111.

VIGLIONE, A. 2009. Non-supervised Regional Frequency Analysis. Version 0.6-9 ed.

WILKERSON, G. V. 2008. Improved bankfull discharge prediction using 2-year recurrence-period discharge. *Journal of the American Water Resources Association,* 44**,** 243-258.

WORTHY, M. 2005. High-resolution total stream power estimates for the Cotter River, Namadgi National Park, Australian Capital Territory. *In:* ROACH, I. C. (ed.) *Regolith 2005-Ten Years of CRC LEME.*

XIAO, X., WHITE, E. P., HOOTEN, M. B. & DURHAM, S. L. 2011. On the use of log-transformation vs. nonlinear regression for analyzing biological power laws. *Ecology,* 92**,** 1887-1894.

Chapter 5 Hydromorphological characteristics of north-eastern Tasmanian rivers

5.1. Introduction

Natural channel form is a function of hydrology and sedimentology within the constraints imposed by bedrock and valley confinement, and the average river channel-system tends to develop in a way to produce an approximate equilibrium between the channel and the water and sediment it must transport (Leopold and Maddock, 1953). As the morphology of the stream channel reflects the hydrological forces that act upon it (Bartley and Rutherfurd, 2005), the geomorphic character and behaviour of rivers also determines the structure of the habitat available for ecological systems (Brussock et al., 1985, Brierley et al., 1999). Both the hydrological and physical processes that shape river channel morphology operate over a number of different scales, with processes operating at a larger scale delimiting the types of fluvial features and processes that can occur at smaller scales (Frissell et al., 1986). Regional scale differences in climate, geology, and topography exert control upon the general geomorphic processes developed upon a landscape (Montgomery, 1999), but the variations in channel cross-sectional morphology at the reach scale are related to macro-scale local factors, including channel pattern, gradient, valley width, tributary inputs and human activity (Thoms, 2006).

This study considered three important parameters that integrate hydrological and geomorphological elements that influence the geomorphic character and behaviour of river channels: drainage density, bankfull stage discharge and frequency, and stream-power. Drainage density indicates how dissected the landscape is by channels, and reflects both the tendency of the drainage basin to generate surface runoff as well as the erodibility of the surface materials (Gabler et al., 2008). Drainage density is also a commonly used factor in multivariate analysis of streamflow models (Post and Jakeman, 1999). Bankfull discharge is an important concept in the analysis of river morphology, flood events and ecological systems (Navratil et al., 2006), because of its assumed channel forming significance (Wolman and Miller, 1960) and because it marks the condition of incipient flooding (Williams, 1978). Also, at discharges above bankfull the channel and floodplain become connected, helping ecosystem maintenance (Bouwman et al., 2013). Stream-power characterises the ability of a river to carry out geomorphic work (Brierley and Fryirs, 2005), and has been found to be an effective measure of the energy available to drive fluvial, geomorphological and ecological change (Graf, 1983, Barker et al., 2008). Each of these three hydromorphological parameters was considered in turn, with their relevance explained and methods for their determination investigated. Where appropriate, the results are considered in relation to those previously found in north-eastern Tasmania and elsewhere. Each of these hydromorphological parameters are also used in the analyses conducted in Chapter 6.

5.2. Drainage density

5.2.1. Introduction

Drainage density (D_d) is the ratio of stream length to catchment area expressed by:

$$D_d = \frac{\sum L}{A_d} \tag{5.1}$$

Where, ΣL is the total length of streams within a catchment and A_d is the drainage area of the catchment, both in units of the same system (Horton, 1945). High values of drainage density indicate a high density of streams. It has been suggested that the density of a stream network is perhaps the most useful single index in relation to drainage basin processes (Gregory and Walling, 1973), and a number of studies have considered the links between D_d, hydrology and geomorphology (for a summary see Pallard et al. (2009)). As an integral characteristic of the drainage network, drainage density can affect the shape of a river's hydrograph during a rain storm and may provide useful indications for flood risk assessment in ungauged basins (Pallard et al., 2009). It is commonly used as a factor in multivariate analysis of streamflow models (Post and Jakeman, 1999) to estimate dissolved solids concentrations (Day, 1983) and as a variable in the calculation of base-flow recession constants (Thomas et al., 2013). Drainage density has been used to estimate sediment yield from catchments (Gregory and Walling, 1968, Day, 1983, Tucker and Bras, 1998) and the spatial structure of river networks influences the morphology of fluvial features (Benda et al., 2004).

Values of drainage density reflect a wide range of factors including the climate patterns, geology, soils and vegetation cover of a catchment (Gordon et al., 2004). While factors such as relief and slope are believed to exert only a relatively slight influence on drainage density

(Carlston, 1963, Chorley and Kennedy, 1971), climate is generally believed to be of major significance (Tucker and Bras, 1998). There is a general consensus that drainage density reflects precipitation characteristics (Gregory and Walling, 1973), and rainfall intensity in particular is believed to be of major importance, as it has been shown that drainage networks tend to be adjusted to maximum rather than to mean runoff (Abrahams, 1972). Other studies have shown a close relationship between drainage density and mean annual flood (Carlston, 1963). Where precipitation is similar, variation in drainage density is related to other catchment characteristics, particularly soil infiltration capacity which has been shown to have a strong association with drainage density (Chorley and Kennedy, 1971).

Historically, the estimation of D_d relied on maps of various scales or aerial photos, and was consequently not fully quantitative. However the development of Geographic Information Systems (GIS) and the use of digital elevation models have improved the ease, accuracy and objectivity with which D_d can be calculated. This study aimed to develop drainage densities for north-eastern Tasmanian catchments and compare those values with other Tasmanian catchments and with values found elsewhere. In addition it aimed to consider the variation in drainage density across Tasmania, and the density of stream relative to stream order. It also aimed to investigate the within catchment drainage density variation, with the Pipers River Catchment used as an example. Reviews of the literature have not revealed any previous studies of the drainage density of Tasmanian rivers and streams conducted using contemporary methods.

5.2.2. Methods

Catchment area, river length and stream order data were obtained through GIS analysis of the Conservation of Freshwater Ecosystem Values (CFEV) dataset (DPIPWE, 2005) which is based on a 1:25 000 drainage network data layer and a 25 m digital elevation model (DPIW, 2008a). Data was clipped to CFEV catchment and sub-catchment boundaries using Arc GIS, and sorted to remove non-river links (links that were designated as pipes or water-bodies e.g. lakes). Drainage density for each catchment, sub-catchment, and the Strahler stream order (SO) was determined using Equation 5.1. The Pipers River can be considered as typical of Northern Tasmanian rivers (Knighton, 1987a), and sub-catchment drainage densities were mapped for the Pipers River Catchment as an example of the general within-catchment drainage density variability of Northern Tasmanian catchments. All analyses are performed for rivers in their current state, as this thesis is concerned solely with contemporary spatial considerations rather than looking at these relationships in an evolutionary context.

5.2.3. Results

Drainage density values for Tasmania, north-eastern Tasmania and individual north-eastern Tasmanian catchments are given in Table 5.1, and the variation in drainage density across Tasmania is illustrated in Figure 5.1. Catchment area ranged from 352.8 km^2 in the little Forester Catchment to just under 3345 km^2 in the South Esk Catchment. Drainage densities for individual north-eastern Tasmanian catchments ranged from 2.98 km/km^2 for the Little Forester Catchment to 1.64 km/km^2 for the Brumbys -Lake Catchment. The average drainage density for north-eastern Tasmania (2.00 km/km^2) is lower than the overall Tasmania drainage density (2.27 km/km^2). Catchments which drained to the coast all had drainage densities higher than 2, while internally draining catchments and the Tamar Estuary had drainage densities less than 2.

Table 5.1. Drainage density values for north-eastern Tasmanian Catchments. Note figures for north-eastern Tasmania do not include the Furneaux Islands.

Catchment	Catchment Area (km^2)	River length (km)	Drainage density km/km^2
Tasmania	69208.66	157076.72	2.27
North-eastern Tasmania	17216.57	34350.82	2.00
Tamar Estuary	1174.22	2163.00	1.84
Pipers	752.39	1536.98	2.04
Ringarooma	973.65	2137.98	2.20
Musselroe-Ansons	993.80	2240.74	2.25
Boobyalla-Tomahawk	644.80	1459.43	2.26
Great Forester-Brid	788.42	2045.64	2.59
George	624.78	1627.06	2.60
Scamander-Douglas	707.09	2029.65	2.87
Little Forester	352.83	1051.18	2.98
Brumbys-Lake	1482.47	2426.06	1.64
Macquarie	2736.69	4548.91	1.66
Meander	1576.57	2729.15	1.73
North Esk	1063.87	1889.49	1.78
South Esk	3344.99	6465.55	1.93
Maximum	3344.99	6465.55	2.98
Minimum	352.83	1051.18	1.64
Mean	1229.76	2453.63	2.17
Standard deviation	843.71	1412.45	0.45

The variation of D_d found across Tasmania (Figure 5.1) showed that the highest values were located in Western regions of Tasmania, with lower values located in the central areas and particularly in the Furneaux Island group located to the North-east of the State.

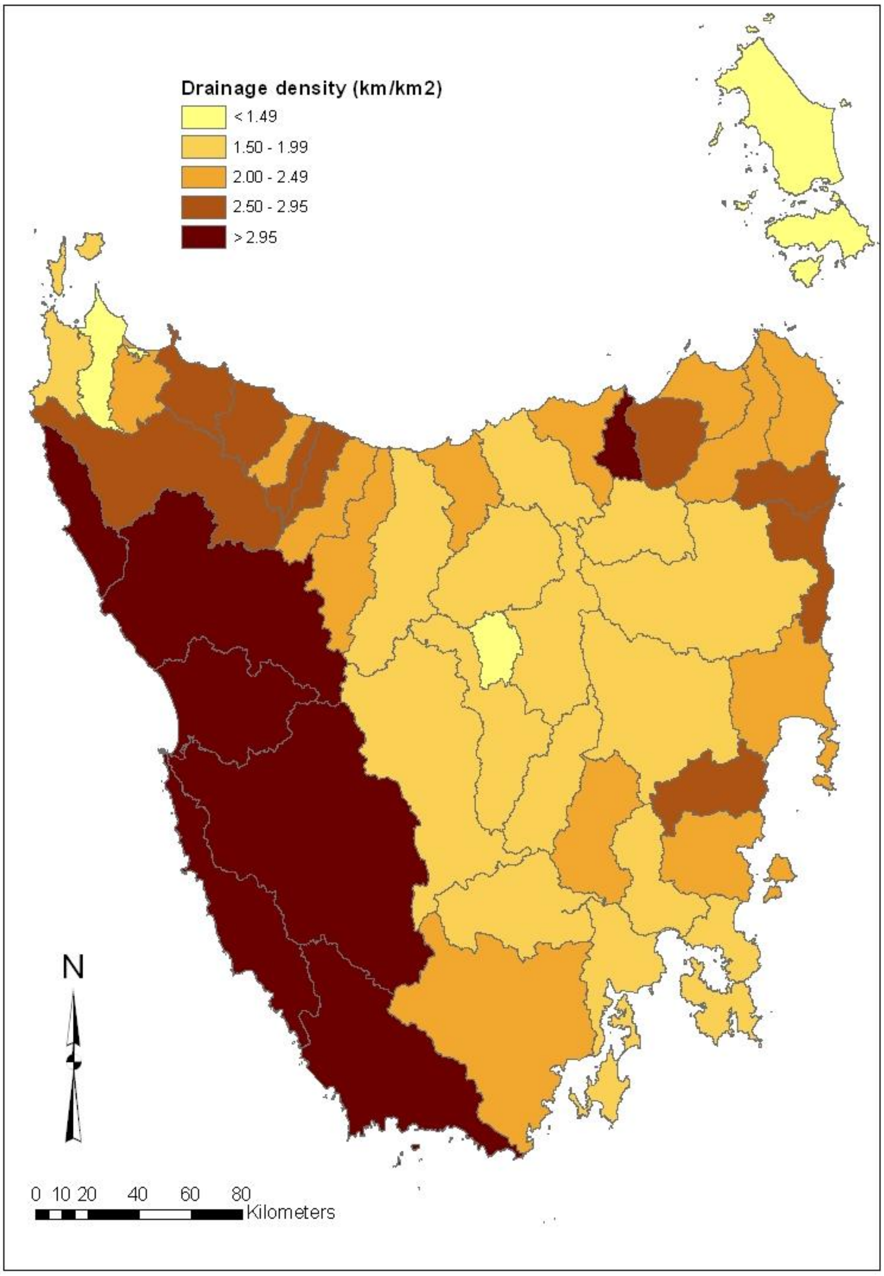


Figure 5.1. Variation in catchment drainage density across Tasmanian (Base layer from CFEV and The List, ©Tasmanian Government).

The variation in the overall D_d of north-eastern Tasmanian catchments is largely the result of the variation in the density of first order streams (Figure 5.2), with little variation in the density of streams of other orders. The Little Forester Catchment had the highest density of first order streams, followed by the Scamander Douglas Catchment. The Furneaux Islands had the lowest density of first order streams, followed by the Brumbys Lake Catchment. The Pipers River catchment with a drainage density of 2.04 km/km^2 (Figure 5.1) was investigated in further detail.

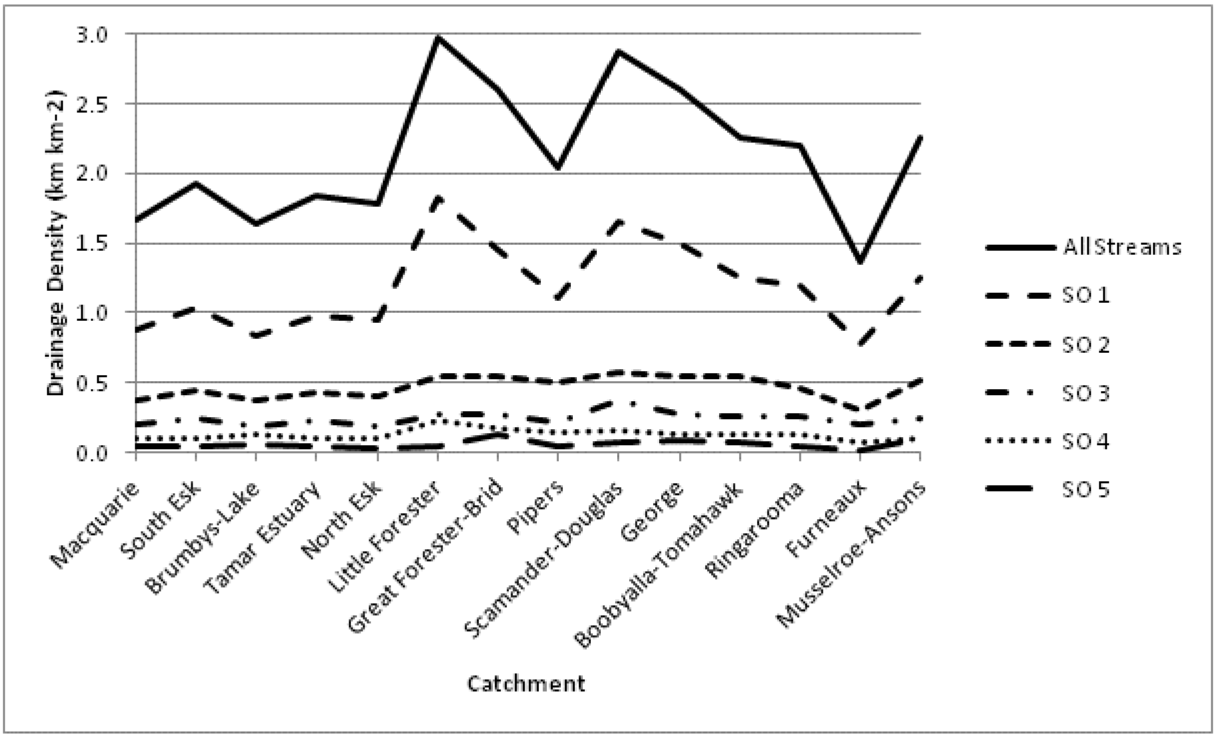


Figure 5.2. Drainage density for north-eastern Tasmanian catchments by stream order (SO). Rivers of SO 6 are not shown.

Drainage density in the Pipers River Catchment ranged from 0.10 in unnamed sub-catchment 42011 to 2.49 km/km^2 in sub-catchment 42002 (Table 5.2). Unnamed sub-catchment 42011 is anomalous as it contains a large dunefield complex. Values for Pipers River sub-catchments were generally lower than the overall Tasmanian drainage density (Figure 5.1). Sub-catchments to the north which are adjacent to the coast (42005, 42007, 42010, 42011 and 42012) showed the lowest drainage density results (Figure 5.3), while those located in the centre of the catchment (42002, 42008) showed the highest drainage density results (Figure 5.3). The D_d values of streams of order 1 to streams of order 6 are also shown. The highest variation in density occurred in first order streams, and many of the sub-catchments lacked streams above stream order 4 (SO4).

Table 5.2. Drainage density (*Dd*) for different stream orders (SO) for Pipers River Catchment and sub-catchments. Each region is shown in Figure 5.3. A_d = catchment area.

Region	**Code**	A_d **(km^2)**	***Dd* (km/km^2)**						
			SO1	**SO2**	**SO3**	**SO4**	**SO5**	**SO6**	**All streams**
Pipers River Catchment		752.39	1.11	0.51	0.21	0.14	0.04	0.03	2.04
Sub-catchments									
Upper Pipers River	42001	209.84	1.12	0.51	0.22	0.16	0.09		2.10
Colgraves Creek	42002	26.88	1.36	0.46	0.33	0.23	0.10		2.49
Pipers Brook	42003	74.62	1.24	0.52	0.21	0.28			2.24
Back Creek	42004	61.99	1.09	0.54	0.18	0.26			2.06
Unnamed	42005	17.72	0.83	0.72	0.06	0.10	0.08		1.78
Unnamed	42006	82.58	1.29	0.56	0.19	0.18	0.05		2.26
Tam O'Shanter Creek	42007	47.85	0.79	0.35	0.10				1.24
Dead Horse Creek	42008	75.98	1.33	0.57	0.23	0.06		0.22	2.41
Turquoise Creek	42009	9.93	1.05	0.26	0.17			0.77	2.24
Little Pipers River	42010	10.77	0.48	0.35	0.83				1.66
Unnamed	42011	10.97	0.10						0.10
Unnamed	42012	35.35	0.82	0.52	0.18	0.02			1.57
Unnamed	42013	87.93	1.12	0.53	0.34	0.07	0.06		2.11

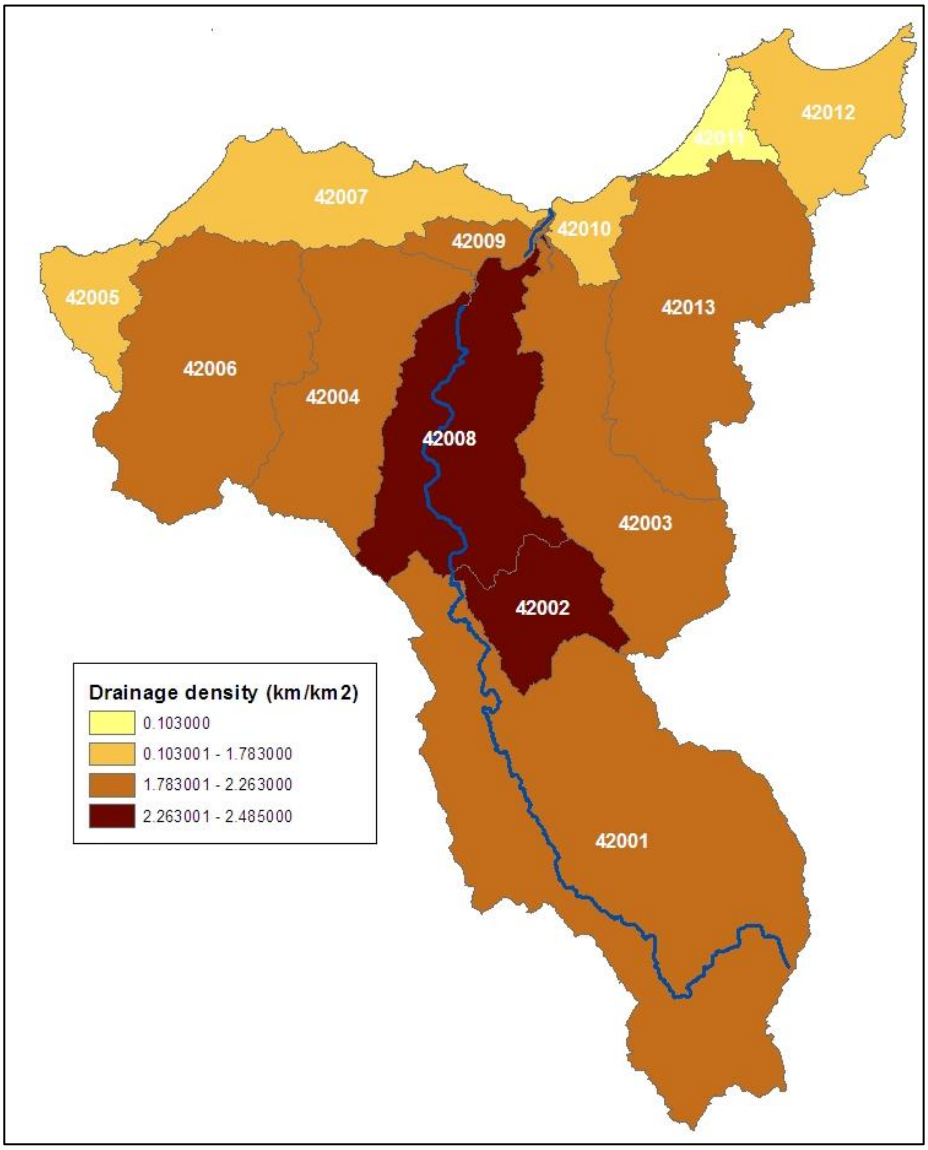


Figure 5.3. Variation in sub-catchment drainage density across the Pipers River Catchment. Sub-catchment names are provided in Table 5.2. (Base layer from CFEV and The List, ©Tasmanian Government).

5.2.4. Discussion

5.2.4.1. Patterns of drainage density

The overall pattern of drainage density across Tasmania (Figure 5.1) closely reflected the State's precipitation patterns (Figure 5.4), with higher values in wetter areas of the west and north-west and lower values in drier areas of the center and eastern coast of the state, located in the rain-shadow of the elevated areas to the west. High values of drainage density and precipitation also occur around the mountains South of Scottsdale and east of Launceston. The close association between precipitation and drainage density has been previously demonstrated (Carlston, 1963, Chorley and Kennedy, 1971, Abrahams, 1972, Tucker and Bras, 1998).

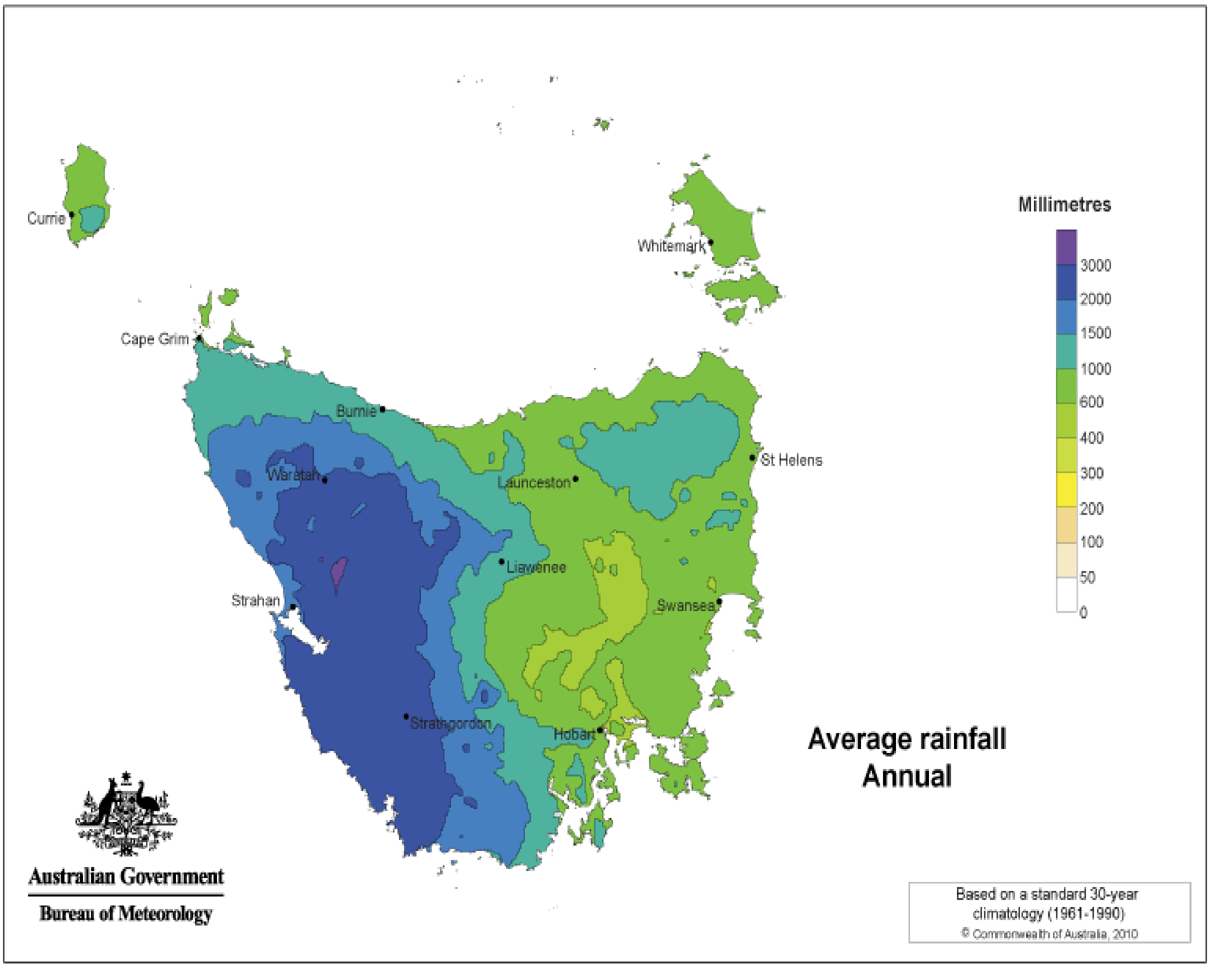


Figure 5.4. The distribution of rainfall across Tasmania (mean annual rainfall 1961 to 1990) (BOM, 2012).

The patterns of D_d also show some correlation with the topography of eastern Tasmania, but less so on the windward western coast (Figure 5.5). While D_d generally increased with increases in elevation, this may be as a result of the correlation between precipitation and elevation, rather than any direct effect of elevation on D_d. The low D_d values of the elevated regions in the lee areas of the centre of Tasmania support this observation, with these areas showing high elevation values but low precipitation (Figures 5.5 and 5.4 respectively). Comparisons of drainage density with relief may provide further insights. The Little Forester Catchment has the highest drainage density of all north-eastern catchments (Table 5.1 and Figure 5.1) but has a generally low elevation (Figure 5.5). However the Little Forester Catchment also has a large portion of its catchment area experiencing high relief. Conversely, the Brumbys-Lake Catchment has the lowest drainage density in the north-east (Table 5.1 and Figure 5.1) but also has high elevation and high relief over substantial portions of its catchment (Figure 5.5). However the Brumbys-Lake also contains sections of the very low relief central highlands which may explain these low drainage density values.

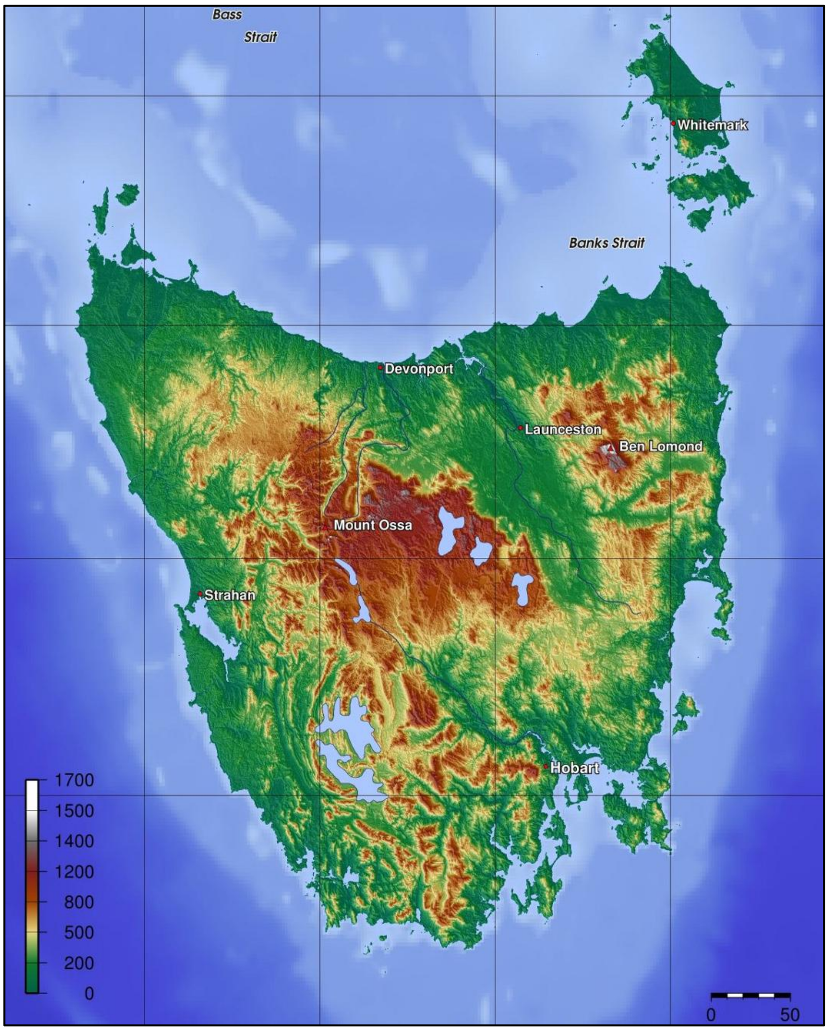


Figure 5.5. Topography of Tasmania, with elevation shown in metres ASL. Source:(Amante and Eakins, 2009).

Comparisons of D_d with surface geology also shows evidence of some correlation. A clear divide in the geology of Tasmania exists between the eastern part of the state which is composed predominately of Parmeener and dolerite materials, as well as Devonian granites and Ordovician Mathinna beds in the north-east, and the mix of materials found in the western part of the state (Figure 5.6). This divide roughly aligns with the change in drainage density between the east and west. Changes in geology in the north-east of the state also align with drainage density changes, however drainage density changes in the south-east have no corresponding change in surface geology.

The lower D_d values in lower elevation north-eastern Tasmania in comparison to Tasmania as a whole (Figure 5.1) are therefore likely to be predominately a result of the lower rainfall in this region. North-eastern catchments with higher drainage densities occur in the elevated area of the north-east highlands, which is also an area of relatively high precipitation (Figure 5.4). The high drainage density variability found in SO1 (stream order 1) streams in north-eastern Tasmanian catchments and the low variability in higher order streams suggest that the majority of variation in D_d across catchments is caused by variation in the number of 1st order streams, and that the density of higher order streams is relatively constant (Figure 5.2).

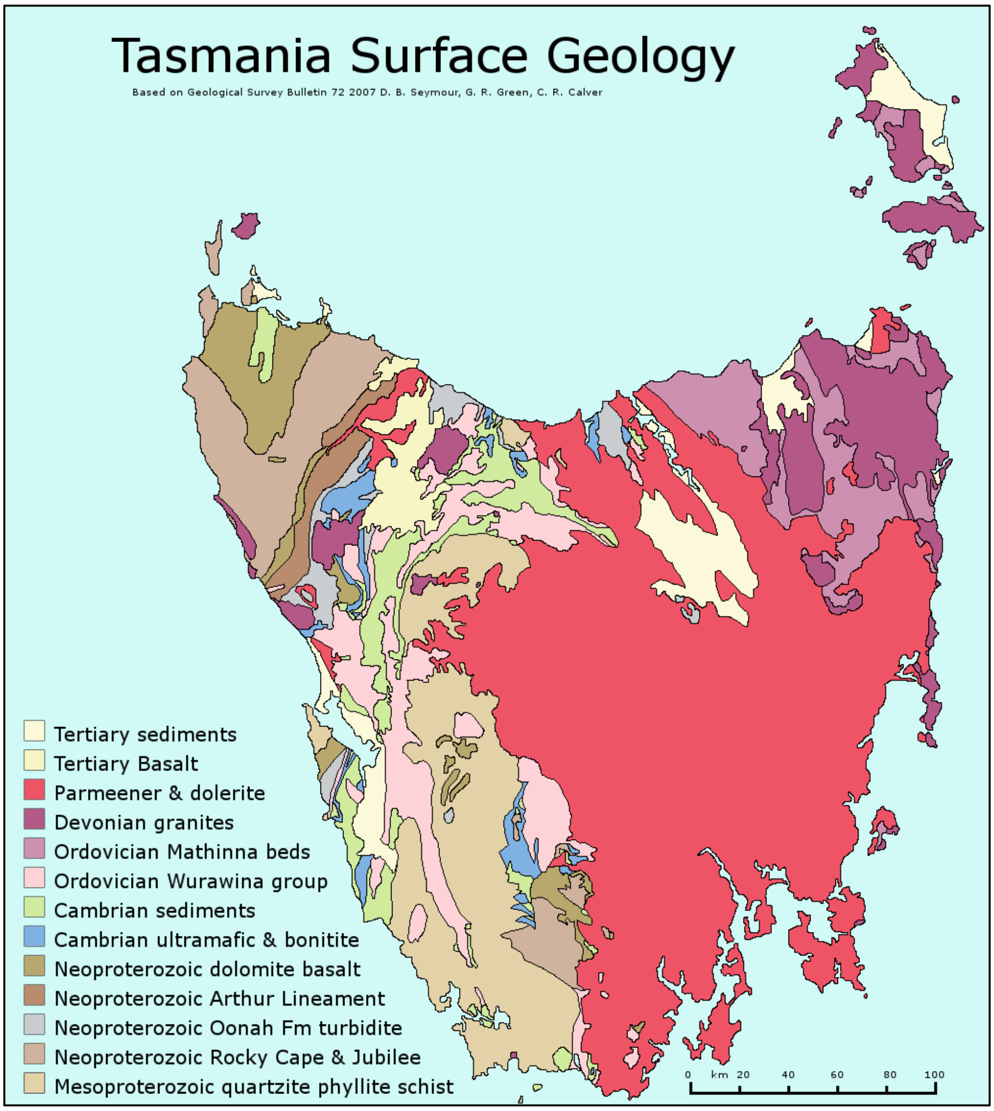


Figure 5.6. Simplified Tasmanian surface geology. (Source: Bartlett, 2008).

The Pipers River Catchment (Figure 5.3) is typical of north-eastern catchments which drain northwards towards Bass Strait, with drainage density values largely reflecting precipitation patterns (Figure 5.4). Higher values in the middle of the catchment may be a result of the elevated local topography. Pipers River sub-catchments with higher values of drainage density also had a larger number of higher order streams (Table 5.2), suggesting that the structure of the stream network may also influence D_d values.

5.2.4.2. Comparisons with other studies

The Tasmanian drainage density values found in this study generally fell in the middle of the range of values found elsewhere (Table 5.3). Although the use of remote sensing and GIS provides relatively accurate and reliable drainage density values, the comparison of drainage densities of different regions has previously had limited success due to the differing standards of data (Gardiner et al., 1977). In addition, drainage density values are contingent upon the scale and approach to analysis, and this limitation should be borne in mind when considering the results of this study to other studies. There are a wide range of drainage density values across the world (Table 5.3), with maximum values greater than 20 reported from some areas (Gregory, 1976), although most values are generally well below this. Abrahams (1972) found drainage density in Australia to be significantly different to that found in America, and postulated that distinct regional drainage densities occur across Australia as a result of variable climatic and floristic characteristics. Results of that study suggested that drainage density in Eastern Australia reached a minimum in areas where mean annual precipitation was between 380 and 635 mm, and continued to increase until a maximum drainage density is reached in areas with around 2,600 mm annually (Abrahams, 1972). However this study found that drainage density continued to increase as precipitation increased past 3,600 mm annually (Figure 5.1 and 5.4).

One of the few estimates of drainage density in north-eastern Tasmania was undertaken by Abrahams (1972), who estimated values for the Musselroe region of north-east Tasmania (Table 5.3). However the value reported of 13.32 mi/mi^2 is difficult to compare with estimates from this study for the same catchment (2.25 km/km^2; Table 5.1) as it was based on extrapolation of a small portion of a 1:31,680 scale map of the area which was composed almost entirely of hillslopes (Abrahams, 1972).

Table 5.3. Estimated drainage densities from selected Australian and international studies (Figures marked * are in mi/mi^2).

Source	Location	Drainage density (km/km^2)
(Horton, 1945)	New York State, US	1.20 - 1.86*
(Troch et al., 2001)	Belgium	1.55
(Douglas, 1977)	Northern Qld.	2.46
(Abrahams, 1972)	NSW	1.8 - 4.9*
(Day, 1983)	Northern NSW, Aust	0.8
(Post and Jakeman, 1999)	Victoria	1.62 - 4.16
(Abrahams, 1972)	Tasmania	7.78 - 13.32
This study	North-east Tasmania	1.64 – 2.98

5.2.5. Conclusion

This study found the pattern of spatial variability of drainage density reflected patterns of mean precipitation and to a lesser extent elevation and surface geology, reflecting that of other studies that have found a strong relationship between precipitation and drainage density. North-eastern Tasmanian catchments which rise from mountainous areas and drain north or east to the coast also showed higher drainage densities then those draining internally to the Tamar Estuary. The range of drainage density values found in north-eastern Tasmania fell within the range of those found elsewhere. However, the close relationship between precipitation and drainage density in this study extended well past the precipitation levels found to coincide with maximum drainage density in other studies. Future investigation of the relationship between drainage density values and factors such as rainfall intensity in north-eastern Tasmania would increase understanding of the causes of drainage density variation in the region and possibly elsewhere. As drainage density reflects both the tendency of the drainage basin to generate surface runoff as well as the erodibility of the surface materials (Gabler et al., 2008), drainage density offers a potential sub-catchment scale remotely sensed parameter in the typology of rivers.

5.3. The frequency of bankfull discharge in Northern Tasmanian Rivers

5.3.1. Introduction

Bankfull discharge may be defined as the discharge above which flow would exceed the active channel banks of a river (Riley, 1972). Used in a range of river related applications, bankfull discharge in alluvial rivers has been linked by some studies to concepts of a dominant or effective discharge, which is largely responsible for channel formation and which occurs at relatively constant frequency along a river and/or across a region. However more recently, both the magnitude and frequency of bankfull discharge have been shown to be highly variable in some rivers and regions (See Section 1.5). Bankfull discharge is commonly estimated through a form of the equation:

$$Q_{bf} = AV \tag{5.2}$$

where Q_{bf} is bankfull discharge (m^3s^{-1}), A is the bankfull cross-sectional area of the stream channel (m^2) and V is the average velocity of flowing water at bankfull (ms^{-1}). Bankfull cross-sectional area is normally determined through analysis of plots derived from cross-sectional surveys of the river channel. Water velocity may be measured using a number of tools, however determining the flow velocity at bankfull is more difficult. Velocity is one of the most sensitive and variable properties of open-channel flow because of its dependence on so many other factors (Knighton, 1998), and being present to measure it at the moment of bankfull discharge is logistically challenging.

In lieu of direct measurement, a number of methods have been developed to estimate the velocity of the flow based on the channel slope and the friction of the channel bed and walls. These equations, generally referred to as flow resistance equations, generally take the form:

$$V = KR^aS^b \tag{5.3}$$

where K is a coefficient, R is the hydraulic radius, S is the friction slope, and a and b are exponents. The most well known and widely used of these models is the semi-empirical Manning's equation (Table 5.4), which uses a resistance coefficient 'n', to relates average flow velocity to the variables of channel form and flow resistance. Manning's 'n' can be considered to be a calibration factor which integrates the effects of flow resistance caused by bed roughness, the presence of vegetation, the amount of sediment or debris carried by the flow and other factors (Chow, 1959). The value of ‘n’ generally decreases significantly at higher discharges, and usually reaches a minimum value at a stage below or approaching bankfull stage (Institution of Engineers Australia, 1987, Gordon et al., 2004).

The accurate estimation of ‘n’ remains a serious difficulty in applying Manning’s equation (Gordon et al., 2004) despite the availability of several guides (e.g. Arcement and Schneider, 1989, Hardy et al., 2005, Land and Water Australia, 2009), as roughness can vary both between reaches and within a given reach as discharge varies. Others have suggested that Manning’s equation usually underestimates flow resistance even in high flows (Ferguson, 2010). In an example of the subjective nature of estimating Manning’s ‘n’, Wilkerson (2008) found differences in bankfull discharge magnitude among 17 sites at which two or more independent estimates of bankfull discharge had been made ranged from 3.9% to 260% with a median difference of 48 %. It has been suggested that Manning’s equation should be used with caution and should not to be the default discharge estimation method (Ferguson, 2010).

Table 5.4. Common flow resistance equations for estimating discharge.

Author	Model		Limitations
Manning (Chow, 1959)	$Q = 1.55A^{1.33} S^{0.05\text{-}0.056\log S}$		
Riggs (1976)	$Q = 1.55A^{1.33} S^{0.05\text{-}0.056\log S}$		
Jarrett (1984)	$Q = 3.10AR^{0.83}S^{0.12}$	(1)	$0.002 \geq S \leq 0.04$ $0.15 \geq R \leq 2.1$
Williams (1978)	$Q = 4.0A^{1.21}S^{0.25}$		
Dingman and Sharma (1997)	$Q = 1.564A^{1.173}R^{0.400}S^{-0.0543\log S}$		

(1) Jarretts original equation (‘n’ = 0.39 $S^{0.38}R^{-0.16}$) substituted into Manning’s equation.

Building on the assumption that channel reach roughness is related to slope in natural channels, Riggs (1976) used multiple regression to develop an equation that eliminated the need for subjective estimates of Manning’s ‘n’, and many others have followed this approach (e.g. Williams, 1978, Jarrett, 1984, Dingman and Sharma, 1997, López et al., 2007) (Table 5.4). While results vary, purely empirical relations without any roughness parameter have been found to perform as well (Riggs, 1976) or better (Ferguson, 2010) than the Manning’s equation with expert estimates of ‘n’.

The difficulty of estimating discharge using flow-resistance equations such as Manning’s is well recognized (Riggs, 1976, Jarrett, 1984, Dingman and Sharma, 1997), and Williams

(1978) identified a number of problems specifically related to their use in estimating bankfull discharge. Few of the equations are designed for predicting bankfull discharge, many do not specify the range of channel and flow conditions, discharge is not the dependant variable in some of the equations, and many are designed for local physiographic regions or restricted conditions (Williams, 1978). Other criticisms of these models include the fact that little attention has been paid to their theoretical basis, or the effect that the severe multi-collinearity has on the parameters fitted through multiple regression (Rupp and Smart, 2007), and that all these models tend to have large variance in the estimate uncertainty (Bjerklie et al., 2005). The equation of Jarrett (1984) (Table 5.4), does not work well for sand-bed rivers; (Ferguson, 2010), while the Riggs (1976) method for estimating discharge was recommended for channels with a uniform cross sectional area.

Where a streamflow gauging station exists, flow data may be analysed to determine bankfull discharge, with the recommended method involving determining bankfull elevation at the gauge and reading the corresponding discharge from the station's rating curve (Williams, 1978, Navratil et al., 2010). However the channel morphology at gauging stations is often modified making the accurate identification of bankfull stage difficult, and the relationship between water level and rate of flow at a gauging station is seldom known with accuracy and this is particularly true for flood flows (Wright and Kemp, 2007).

Where the frequency of bankfull discharge is known, bankfull discharge at ungauged locations may be estimated through the development of regional models. The frequency of bankfull discharge is commonly expressed as the average recurrence interval of bankfull stage (T_{bf}), which is the average length of time between two floods of bankfull stage or larger. Wolman and Leopold (1957) suggested that there was a uniform average recurrence interval of bankfull stage discharge (T_{bf}) among many rivers of all sizes in diverse physiographic and climatic regions. Based on the results from a large number of studies in the United Sates, they suggested bankfull discharge had an average recurrence interval of between 1 and 2 years (Wolman and Leopold, 1957).

Despite a number of studies disputing the constant frequency of bankfull discharge (Williams, 1978, Knighton, 1998), the estimation of T_{bf} has become the focus of a large amount of research in fluvial geomorphology, with sometimes widely divergent figures found. Based on streamflow data from 36 stations in the western US, Williams (1978) found bankfull discharge frequency to range from 1.01 to 32 years on the annual series, and Bent (2013) found T_{bf} averaged 1.53 years (median value 1.34 years) at 33 sites in Massachusetts.

Studies of the average recurrence interval of bankfull discharge in Australia have also provided a large range of values (Table 5.5). Dury (1963) suggested that there was equivalence among bankfull flow, channel forming flow, dominant discharge and (confusingly) most probable annual flood, and from a study of Queensland rivers found T_{bf} = 1.6 years. Woodyer (1968) suggested that floodplains and the high bench on incised rivers in NSW belong to the same frequency distribution that he called the present floodplain level, and suggested that for these rivers T_{bf} was 1.24 - 2.69 years (annual maximum series). Bankfull frequency in the Northern Territory has been found to range from less than 2 to 10 years, with an average of 5 years (partial series) (Rustomji, 2009). De Rose et al. (2008) estimated median T_{bf} of 93 sites in Victoria at 0.8 years, with 75% of sites lying between 0.5 and 2.5 years. In a study of the Lachlan River in south-east Australian Kemp (2010) found T_{bf} ranged between 1.9 and 9 years, with return periods generally increasing on both anabranches and single channels downstream.

Table 5.5. Average recurrence interval of bankfull discharge (T_{bf}) from selected studies in Tasmania and elsewhere in Australia.

Study	Location	T_{bf} (years)
(Kemp, 2010)	S.E. Australia	1.9 - 9
(Rustomji, 2009).	NT	< 2 - 10
(Dury et al., 1963)	Qld	1.6
(De Rose et al., 2008)	Vic	0.5 - 2.5
(Woodyer, 1968)	NSW	1.24 - 2.69
(Knighton, 1987b)	N.E. Tas	1.11 - 2

Few studies have considered the frequency of bankfull discharge in Tasmania. Using data from streamflow stations in north-eastern Tasmania, Knighton (1987a) found T_{bf} to lie somewhere between 1.11 and 2 years, with a tendency toward the latter. In a study of three sites in the upper Ringarooma catchment, T_{bf} was estimated at 1.5, 3.1 and 2.1 years (DPIW, 2008b). Other studies of the north-eastern Tasmanian Break O'Day River (Prosser et al., 2000) and Pipers River (Graham, 1999) have adopted T_{bf} = 1.58 and 2 years respectively, but this was based on common practice rather than any imperial evidence.

5.3.2. Results:

Attempts to determine bankfull discharge at ungauged sites for this study using field measurements were generally unsuccessful; after several attempts, the field estimation of flow velocity was determined as impractical due to the inadequacy of the sampling apparatus for the conditions, the high hydraulic variability experienced, and the time required to carry out the procedure. Attempts to determine bankfull discharge through flow resistance equations had mixed results. Bankfull discharge estimates for 28 sites on north-eastern Tasmanian rivers using the methods of Riggs (1976), Jarrett (1984) and Dingman and Sharma (1997) varied considerably (Table 5.6). The estimate of bankfull discharge using the flow equation of Dingman was generally the smallest estimate, with the method of Riggs most often providing the largest estimate of bankfull stage. There were large variances between estimated bankfull discharge using the three methods for some sites, with *CV* ranging from 0.09 to 0.80 and a mean *CV* of 0.21 (Table 5.6).

Table 5.6. Site details of Catchment Area (km^2), Hydraulic Radius (R) (m) and slope (S) (m/m) as well as estimated bankfull discharge (m^{3}s^{-1}) using the flow resistance equations of Riggs (1976), Jarrett (1984) and Dingman (1997). Also shown is the coefficient of variation (CV) between the three methods.

Site Number	Catch Area (km^2)	R (m)	S (m/m)	Discharge (m^{3}s^{-1})			CV
				Riggs[1]	Jarrett[2]	Dingman[3]	
1	138.89	1.21	0.001563	18.70	29.75	18.46	0.29
2	72.60	0.77	0.006456	13.94	13.61	11.54	0.10
3	101.94	0.80	0.006661	31.47	25.87	24.03	0.14
4	397.92	0.91	0.001705	14.55	19.11	13.16	0.20
5	191.99	0.85	0.002071	24.26	32.89	22.52	0.21
6	333.99	1.13	0.001212	23.59	35.79	22.43	0.27
7	64.62	1.59	0.005115	19.27	19.49	16.13	0.10
8	195.27	1.17	0.002437	34.69	55.77	35.27	0.29
9	311.35	0.51	0.001	4.84	5.62	3.99	0.17
10	169.31	0.68	0.005844	15.27	13.41	11.98	0.12
11	389.06	1.50	0.00157	46.93	70.98	45.29	0.26
12	220.95	1.42	0.005526	16.13	11.56	11.46	0.20
13	253.44	0.54	0.005492	57.36	66.86	51.60	0.13
14	360.32	1.42	0.011697	74.10	75.48	63.52	0.09
15	72.79	0.97	0.011286	25.67	25.96	21.88	0.09
16	204.26	1.74	0.002521	28.51	39.29	26.94	0.21
17	51.17	1.25	0.019847	29.01	26.18	23.52	0.10
18	198.43	1.02	0.001311	32.55	62.73	34.91	0.39
19	878.08	0.71	0.001628	49.45	55.29	41.35	0.14
20	268.19	1.04	0.001853	27.24	34.05	24.18	0.18
21	51.36	0.92	0.008146	16.21	14.01	12.72	0.12
22	277.82	0.70	0.003883	42.70	38.85	33.67	0.12
23	441.11	1.07	0.007331	35.54	25.09	25.28	0.21
24	268.02	2.13	0.002532	77.49	129.31	80.46	0.30
25	1023.34	1.72	0.000901	60.21	105.00	60.10	0.34
26	1360.45	2.14	0.0001	31.46	123.77	37.78	0.80
27	136.09	0.78	0.001154	13.03	16.48	11.30	0.19
28	4.42	0.33	0.003402	0.65	0.72	0.56	0.13

1. $Q = 1.55A^{1.33}\,S^{0.05\text{-}0.056\log S}$ (Riggs, 1976)
2. $Q = 3.10AR^{0.83}S^{0.12}$ (Jarrett, 1984)
3. $Q = 1.564A^{1.173}R^{0.400}S^{-0.0543\log S}$ (Dingman and Sharma, 1997)

5.3.3. Discussion:

The estimation of bankfull discharge at an un-gauged location to any degree of accuracy requires field measurements during bankfull stage flood events. However the substantial resources required to gauge these flood events tend to make this method impractical. Rating curves linking stage to discharge can also be used to estimate bankfull discharge, but require a range of different magnitude at-site discharge estimates. Taking field measurements during lower discharges can also be resource intensive, and includes conducting cross-sectional surveys of the river channel, and measurement of velocity at different points both across the width of the channel and along the reach. The measurement of velocity is complex, with the method generally varying dependant on the stream type. After preliminary investigations, measuring bankfull stage velocity or establishing rating curves was found to be impractical to gain meaningful data for this study with the time, equipment and other resources available. Bankfull flows for many of the study rivers produced conditions unsafe for making handheld velocity measurements. At lower flows, difficulties were encountered using flow meters in the smallest streams due to the diameter of the impeller being greater than the stream depth. Larger streams required the use of a boat for velocity measurements due to their depth, and as a substantial number of different measurements would be required to construct a rating curve, the logistics meant this method was abandoned. As a consequence, the estimation of bankfull discharge using flow resistance equations was investigated, but this also proved problematic, with the large variability between methods found in the results from this study (Table 5.6 and Figure 5.7) compounding the uncertainty in estimates that each of these models display (Bjerklie et al., 2005).

The three estimates of bankfull discharge for the 28 sites are plotted along with CV in Figure 5.7. While sites with high *CV* tended to have high Q_{bf}, sites with high Q_{bf} did not necessarily have high CV. The highest values of *CV* occurred when Jarrett's estimates were significantly higher than the other two estimates. The best predictor of high *CV* was high hydraulic radius (R) (Table 5.6), suggesting that estimates were more closely clustered on deeper channels and were more divergent when the channel was shallower. The two sites with the both the largest catchment area and the smallest slope (Sites 26 and 25) had the largest and third largest *CV* values respectively, however the site with the second highest *CV* (Site 18) had a relatively small catchment area and the sixth smallest slope.

The divergence of discharge estimates on deep channels with high R values is likely to be because all three flow equations are developed on the assumption that channel reach roughness is related to slope in natural channels. The relationship between reach roughness and slope has less relevance in deeper channels where the drag of water against the channel bed has proportionally less effect on flow than in shallower channels. High values of R indicate a small wetted perimeter in relation to cross-sectional area and an 'efficient' channel where discharge is less exposed to the roughness of the channel. Consequently it is suggested that the range of conditions for the use of these equations should be limited by high values of *R*.

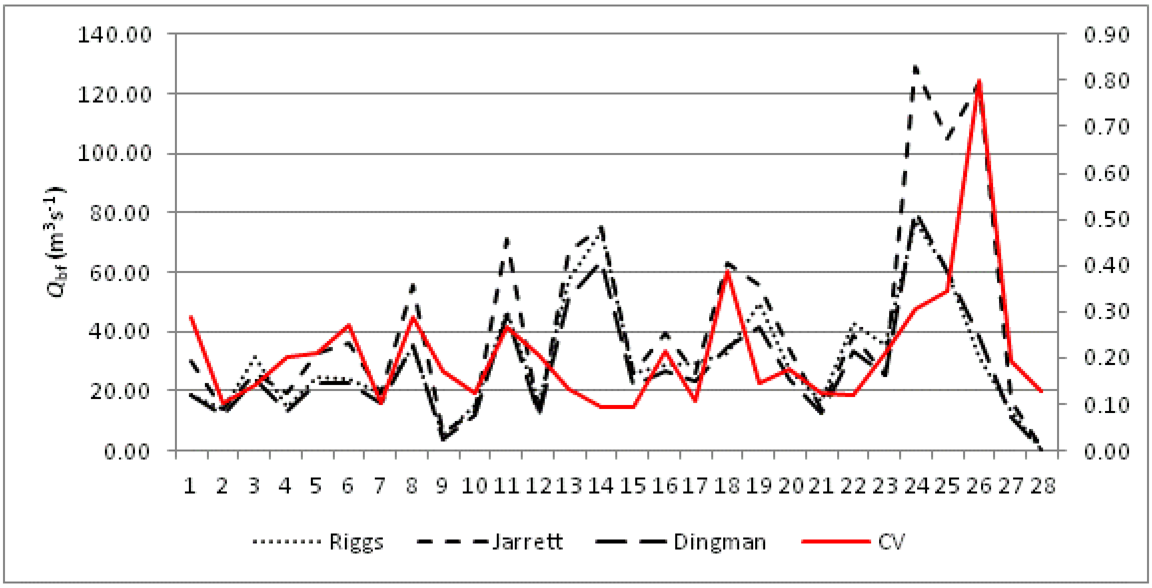


Figure 5.7. Estimated bankfull discharge using the flow resistance equations of Riggs (1976), Jarrett (1984) and Dingman (1997), as well as the coefficient of variation (*CV*) between the three methods.

The mean of the three different bankfull discharge estimates for each site is plotted against catchment area in Figure 5.8. The majority of sites had catchment areas below 500 km^2, and three sites had catchment areas greater than 800 km^2 (Table 5.6 and Figure 5.8). The site showing the largest deviation above the trend line is that of the Scamander River upstream of Scamander water intake, followed by the North Esk River at Ballroom. The Scamander river site has previously been found to plot as a positive residual in the relationship between catchment area and discharge for north-eastern Tasmania (Section 4.4.3). The sites furthest below the trend line are the Isis River at Isis and the Third River at Paling Track. The Third River site understandably deviates from the trend line due to its very small catchment area.

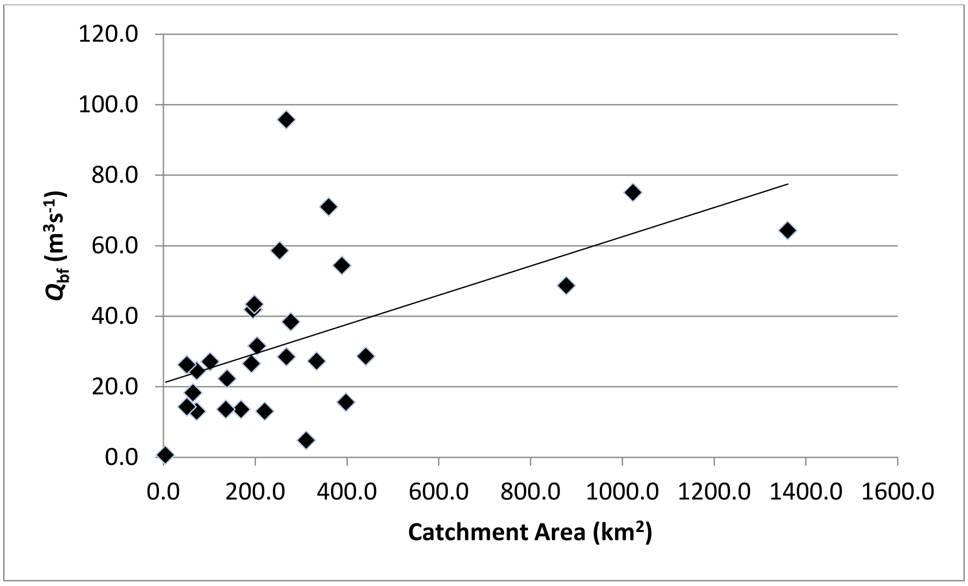


Figure 5.8. Mean estimated bankfull discharge of the flow resistance equations of Riggs (1976), Jarrett (1984) and Dingman (1997), plotted against Catchment Area (km2) with a linear trendline fitted.

Estimates of the average recurrence interval of bankfull discharge in north-eastern Tasmanian rivers have ranged between 1.1 and 3.1 years, which is in the range of that found in other studies (Table 5.5). However definitions of bankfull stage, and consequently bankfull discharge, vary (See Chapter 3), and bankfull discharge frequency has been found to be highly variable. Even when developing the concept of a uniform bankfull discharge recurrence frequency, Wolman and Leopold, (1957) identified that results from mountain streams where the floodplain was restricted did not fit the general pattern. The extent, type and condition of riparian vegetation and the presence of large woody debris can also affect bankfull frequency. Riparian vegetation has been shown to influence channel morphology (e.g. Millar, 2000; Pietsch and Nanson, 2011) meaning that sections of river with intact riparian vegetation may have different bankfull discharge frequency to sections of river without vegetation or with different types or extent of vegetation. In the swamp forests in north west Tasmania for example, vegetation is so effective at trapping and stabilising sediment that the channel capacity is very small and bankfull floods occur much more frequently than once every one or two years (Jerie et al., 2003).

Page et al. (2005) suggested that a significant component of the geographic variability in bankfull discharge frequencies may occur as a result of river regulation, with the regulation of flows on the Murrumbidgee River halving the frequency and duration of bankfull flows.

De Rose et al. (2008) found decreasing T_{bf} with increasing catchment area, with substantially lower values on mid to lowland reaches than on upland reaches.

Channel morphology also plays a role in bankfull frequency. Channel slope has been identified as affecting bankfull frequency, with a general trend for the recurrence interval to increase (longer periods between bankfull flows) as slope steepens (Williams, 1978). Other factors such as the flood frequency analysis method, data type and data quality can also affect bankfull discharge frequency values, and the uncertainty introduced by these factors make comparisons of results from different studies difficult (Williams, 1978, Navratil et al., 2006). Furthermore, there are sources of error associated with all common methods for estimating bankfull discharge (i.e., rating curve, flow recurrence frequencies, and flow resistance equations) (Williams, 1978).

5.3.4. Conclusion

Attempts to accurately measure bankfull discharge at the study sites using field techniques were unsuccessful. The use of commonly used flow resistance equations to predict bankfull discharge was also found unsuitable as the large variances found between estimates from different flow resistance equations, particularly at sites with deeper channels and high hydraulic radius, made the use of these methods uncertain. Previous studies have estimated that the average recurrence interval of bankfull discharge in north-eastern Tasmanian rivers falls between 1.11 and 3.5 years. Although bankfull discharge magnitude frequency is unlikely to be constant along a river or throughout a region, discharge with a 2 year average recurrence interval has been adopted as a proxy for bankfull discharge or dominant discharge in many other studies (e.g. Barker et al., 2008, De Rose et al., 2008). Consequently, it is recommended that 2 years is a suitable approximation to adopt for the average recurrence interval of bankfull discharge in north-eastern Tasmanian rivers.

5.4. Stream Power

5.4.1. Introduction

Stream power (Ω) defined as the product of water density, flow rate and water surface slope (Bagnold, 1977), and may be determined by the equation:

$$\Omega = \rho g Q_{bf} S \tag{5.4}$$

Where ρ is the density of water (1000 kgm^{-3}), g is the gravitational constant (9.8 ms^{-1}), Q_{bf} is bankfull discharge (m^{3}s^{-2}) and S is slope (m/m). Stream power expresses the rate of potential energy expenditure per unit of channel length. It characterises the ability of a river to carry out geomorphic work (Brierley and Fryirs, 2005, Jain et al., 2006), however the work actually accomplished also depends upon the efficiency with which energy can be transmitted from the flowing water to the sediment (Church, 2002).

Stream power has been shown to have an important influence on channel morphology (Montgomery and Buffington, 1997, Knighton, 1999, Reinfelds et al., 2004, Schmitt et al., 2007, Orr et al., 2008), and is appropriate to differentiate between variants of river settings (Brierley and Fryirs, 2005) and to develop predictive hydromorphological typologies (Schmitt et al., 2007, Orr et al., 2008). Kondolf et al. (2003) have pointed out that different classes of stream-powered river classifications frequently overlap, although the lack of clear stream power thresholds between channel patterns has been attributed to difficulties in the estimation of basic parameters (Ferguson, 1987). As stream-power affects sediment transport capacity and has a controlling influence on several aspects of channel morphology, the way in which it varies downstream has important implications for the distribution of process activity and channel adjustment within the fluvial system (Knighton, 1999).

5.4.2. Methods

While a range of methods have been used to conduct stream-power studies, the use of remotely sensed data and GIS systems to model stream-power over large-scales is now the most common procedure, largely because it can be applied over broad areas without the need for detailed knowledge of stream characteristics (Finlayson and Montgomery, 2003). Many of these GIS based studies use relative stream-power values to illustrate the pattern in stream-power distribution (Finlayson and Montgomery, 2003, Jain et al., 2006, Pérez-Peña et al., 2009). While other more complex approaches are possible, the advantage of this approach is that it provides a better approximation to real data (Jain et al., 2006).

This study modeled stream-power for each river link (section of river between confluences) in north-eastern Tasmania using Equation 1. Following common procedure (Knighton, 1999, Jain et al., 2006, Pérez-Peña et al., 2009), bankfull discharge (Q_{bf}) was modeled as a power-law function of catchment area (A_d) (See Chapter 4), with two years adopted as the average recurrence interval of bankfull discharge (See Section 5.3). Selecting the appropriate equivalent equation from Chapter 4 provides:

$$Q_{bf} = 0.45\, A_d^{0.9} \qquad (5.5)$$

Catchment area and slope for each river link was determined from the Tasmanian Conservation of Freshwater Ecosystem Values (CFEV) data set (DPIPWE, 2005). Gippel (1985) suggests that the most geomorphologically meaningful expression of channel slope is the energy profile at bankfull flow, which may be approximated by low flow surface water slope. However, the values for *S*, the slope of the water, are generally approximated by the slope of the channel bed (Pérez-Peña et al., 2009). As CFEV slope values are based on the change in elevation over the length of the river link derived from a 25 m digital elevation model (DPIW, 2008a), it can only be a rough approximation of the true value of *S*. Where the CFEV dataset recorded a zero value for *S*, river links were modified (+ 0.00001) for ease of analysis.

5.4.3. Results

Plots of the longitudinal distribution of stream-power in the Pipers, Ringarooma and Scamander Rivers against accumulated catchment area and elevation are shown in Figures 5.9, 5.10 and 5.11 respectively. Also shown are representative cross-sectional channel profiles from selected reaches along each river. While channel morphology was often highly variable along a reach, these cross-sections were selected as being typical of river channel width and depth at each location.

Stream-power in the Pipers River was highly variable, and ranged from 0 to in excess of 24 000 Wm^{-1}(Figure 5.9. D). Within the variability, there was a general trend for stream-power to increase up to around 10 km from the source of the Pipers River before decreasing to around 35 km and then increasing again towards the mouth of the river. Over the first 20 km from the source of the Pipers River, the elevation changed from in excess of 700 m ASL to just over 100 m ASL, while over the next 20 km the elevation of the Pipers River changed less than 50 m (Figure 5.9.D). Accumulated catchment area showed a gentle rate of increase over the upper 25 km of the river before increasing at a much greater rate reaching in excess of 300 km^2 at the mouth of the river. Relatively large increases in catchment area coincided with tributary junctions (Figure 5.9.D).

Site A (Pipr020-Pipers River at Underwood) is a partially confined reach located 11.1 km from source at 267 m ASL (Figure 5.9.D). Catchment area is relatively small at 51.2 km^2. The channel profile at this site is typical of those found on a bend in a meandering river with a relatively steep bank on the left hand side and a sloping channel bank on the right (Figure 5.9.A). The channel at this location has a moderate width-to-depth ratio (14.3) and hydraulic radius (0.9). Stream power for this site was estimated at 3023.2 Wm^{-1}, with nearby reaches generally ranging from 2000 to 4000 Wm^{-1}.

Site B (Pipr060-Pipers River downstream of Colgraves Road) is a partially confined reach located 32.1 km from source at 64 m ASL (Figure 5.9.D). Catchment area is moderate at 198.4 km^2. The channel profile at this site is quite deep in relation to its depth (Figure 5.9.B), with a small width-to-depth ratio (6.25) and a large hydraulic radius (1.74). Stream power for this site was estimated at 680.5 Wm^{-1}, with nearby reaches generally ranging from 5 to 1800 Wm^{-1}.

Site C (Pipr075-Pipers River at Lewis Road Bend) is a partially confined reach located less than 5 km downstream of site B at 36.9 km from source (Figure 5.9.D). It is located at an elevation of 59 m ASL and has a catchment area of 204.3 km^2. The channel profile at this site has a smaller cross-sectional area than the upstream Site B (Figure 5.9.B), with a moderate width-to-depth ratio (10.71) and hydraulic radius (1.25). Stream power for this site was estimated at 1339.3 Wm^{-1}, with nearby reaches generally ranging from 2000 to 4000 Wm^{-1}.

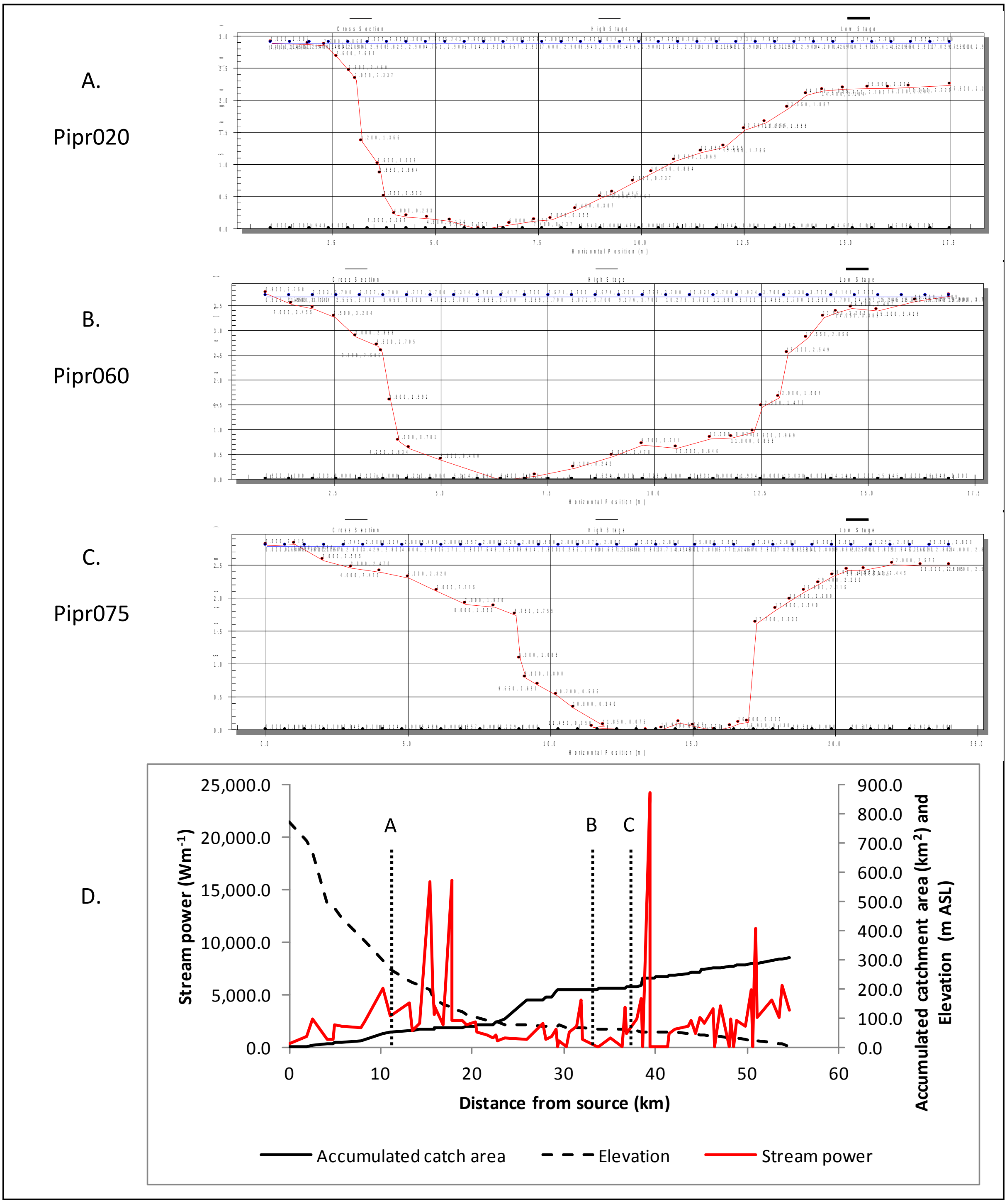


Figure 5.9. Stream power, catchment characteristics and channel morphology variation in the Pipers River: A) cross sectional river channel profile at the Pipers River at Underwood; B) cross sectional river channel profile at the Pipers River below Colgraves Road: C) cross sectional river channel profile at the Pipers River at Lewis Road Bend; and D) downstream variation in stream-power, accumulated catchment area and elevation for the Scamander River, with location of cross sectional river channel profiles marked.

Stream-power in the Ringarooma River was also highly variable, with values ranging from 0 Wm^{-1} to in excess of 14 000 Wm^{-1} (Figure 5.10.E). There was a general trend for stream-power values to increase up to around 80 km from its source, before declining towards the mouth of the river. Site A in Figure 5.10 (Ring015-Ringarooma River off Maurice Road) is a partially confined stream reach located 15.8 km from the river source at 265 m ASL (Figure 5.10.E). It has a small accumulated catchment area (51.4 km^2) and as it is located below the sharp rise in elevation associated with the surrounding mountain range, channel slopes are generally moderate. Consequently, most river reaches in this region have moderate stream power (approx. 1,000-2,000 Wm^{-1}), with stream-power for the study reach estimated at 1245.8 Wm^{-1}. The bankfull channel is quite narrow and deep (Figure 5.10.A) with a low hydraulic radius (0.71) and a moderate width-to depth ratio (19.21).

Site B (Ring 050-Ringarooma River at Yeates Property) is located 27.8 km from source and at 200 m ASL (Figure 5.10.E), and is also a partially confined reach. Catchment area is moderate (268.2 km^2). The channel is wider and deeper than at site A (Figure 5.10.B) and has quite a high width-to-depth ratio (19.15) and a moderate hydraulic radius (1.04).Stream power for this site was estimated at 1259.7 Wm^{-1}, with nearby reaches generally ranging from 1000 to 4000 Wm^{-1}.

Site C (Ring070-Ringarooma upstream of Bakers Creek) was located 43.3 km from source. It had a catchment area of 441.1 km^2 and was 138 m ASL (Figure 5.10.E). The river channel here is considerably wider than at site B but also shallower (Figure 5.10.C), with a very high width-to depth ratio (40.75) and a low hydraulic radius (0.70). Estimated stream power for this reach was very high at 7767.6 Wm^{-1} with nearby reaches ranging from 1500-8,000 Wm^{-1}.

Site D (Ring080-Ringarooma River at Wetlands) is located 94.7 km from the source, at 6 m ASL and 878.1 km^2 (Figure 5.10.E). While stream power for this reach was estimated at quite high value of 3220 Wm^{-1}, many nearby reaches had very low stream power (20 Wm^{-1}). The stream channel at this location is still wide and shallow (Figure 5.10.D), but less wide than at the upstream site C, and with a more complex channel shape. It has a high width to depth ratio (31.7) and a moderate hydraulic radius (1.07).

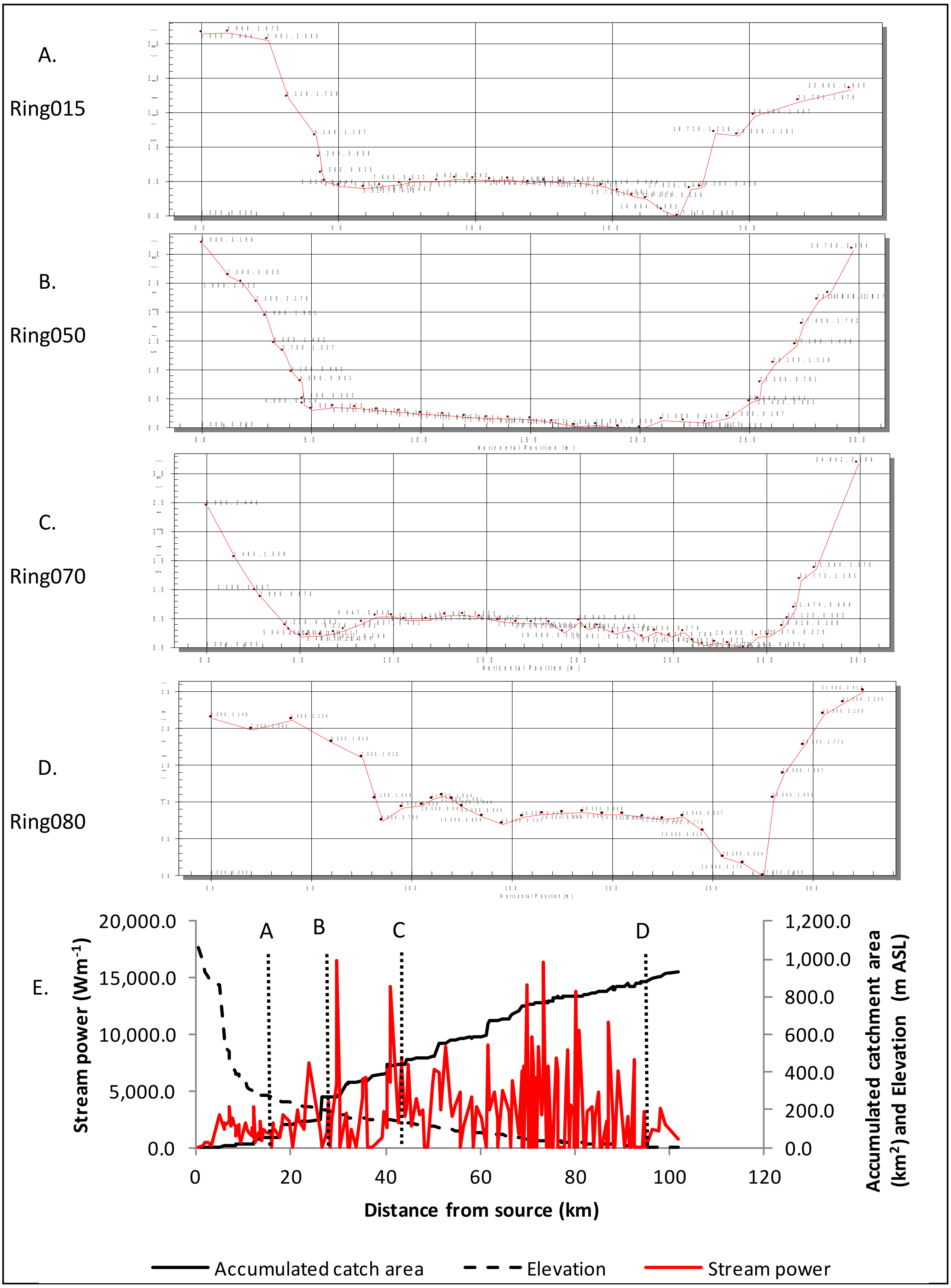


Figure 5.10. Stream power, catchment characteristics and channel morphology variation in the Ringarooma River: A) cross sectional river channel profile at the Ringarooma River at Maurice Road; B) channel profile at the Ringarooma River at Yeates; C) channel profile at the Ringarooma River upstream of Bakers Creek; D) channel profile at the Ringarooma River at wetlands; and E) downstream variation in stream-power,

accumulated catchment area and elevation for the Ringarooma River, with location of cross sectional river channel profiles marked.

Stream-power of the Scamander River was much less variable than that of the Pipers and Ringarooma Rivers, and ranged from 0 to just under 2000 Wm^{-1} (Figure 5.11). There were no strong trends in downstream stream-power patterns, but there was a small general increase around 25 km from the source of the river. Accumulated catchment area increased very slowly until the Avenue River merges with the Scamander River at around 27 km from source. Elevation drops dramatically from over 600 m ASL at around 5 km from source to around 150 m at 8 km from source (Figure 5.11).

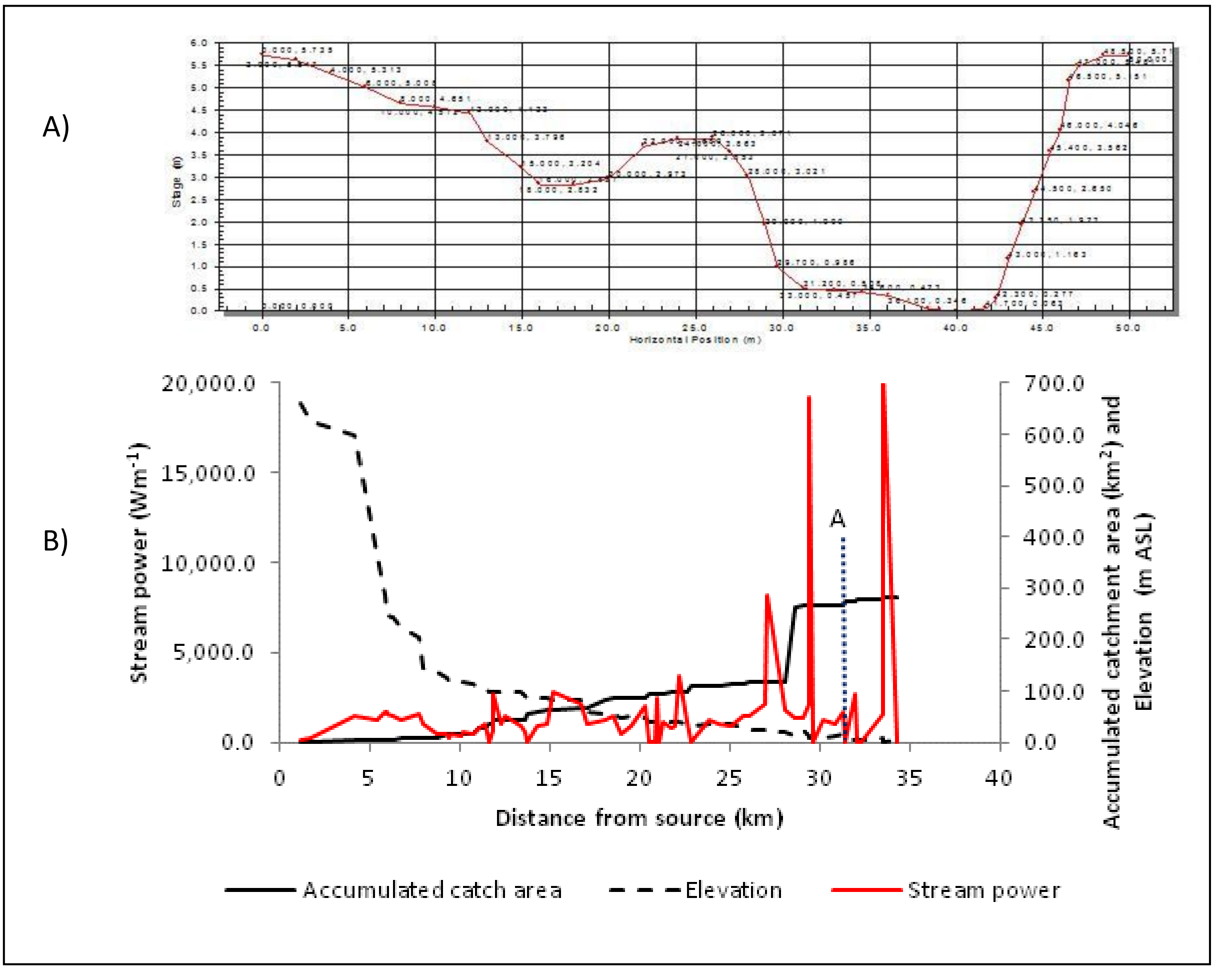


Figure 5.11. Stream power, catchment characteristics and channel morphology variability in the Scamander River: A) cross sectional river channel profile at the Scamander River upstream of Scamander Water Supply; and B) downstream variation in stream-power, accumulated catchment area and elevation for the Scamander River, with location of cross sectional river channel profile marked at A.

Site A (Scamander River upstream of Scamander water supply) is located 31.3 km from the source, at 15 m ASL and with a catchment area of 268 km^2 (Figure 5.11.B). Stream power for this reach was estimated at 1717.8 Wm^{-1}, with nearby reaches in the range of 1000-2000 Wm^{-1}. The stream channel at this location is quite narrow and deep and clearly displays a flood chute on the left bank (Figure 5.11.A). It has a high width to depth ratio (18.61) and a high hydraulic radius (2.13).

5.4.4. Discussion:

In considering the downstream variation in stream-power, Knighton (1999) suggested that stream power tends to peak mid basin, with the exact location dependent on the relationship between rate of change of discharge and rate of change of slope. The patterns of downstream variation in stream-power for the three rivers in this study were each quite different, with none having mid-basin peaks or matching the idealized downstream pattern of stream-power variation suggested by Barker et al. (2008) (Figure 5.12).

The Pipers River showed an upstream maximum located relatively close to the idealized peak, however it also experiences a large increase in stream-power values low in the catchment (Figure 5.9.D). This is likely to be due to a combination of increases in discharge due to the confluence of relatively large tributaries in this section of the river and relatively high slope values. The Ringarooma River showed a stream-power maximum much lower in the catchment (Figure 5.10.E) than both the idealized peak and that of the Pipers River, and unlike the Pipers River the Ringarooma showed a general decrease in stream-power values in its lowest reaches. The Scamander River showed a downstream pattern unlike either the Pipers River or the Ringarooma River (Figure 5.11.B), showing relatively constant stream-power values apart from a number of peaks in the lower sections of the river.

Downstream changes in stream-power are likely to vary considerably even between streams within a single watershed because of different patterns of flow addition but largely because of variations in slope at the profile and local scales (Knighton, 1999). Other studies of Australian rivers have also shown departures from the theoretical mid-catchment peak of stream power (e.g. Worthy, 2005). Knighton (1999) found that stream network peculiarities could also influence the location of the stream-power maximum through their influence on discharge, and this may influence the stream power patterns found in this study.

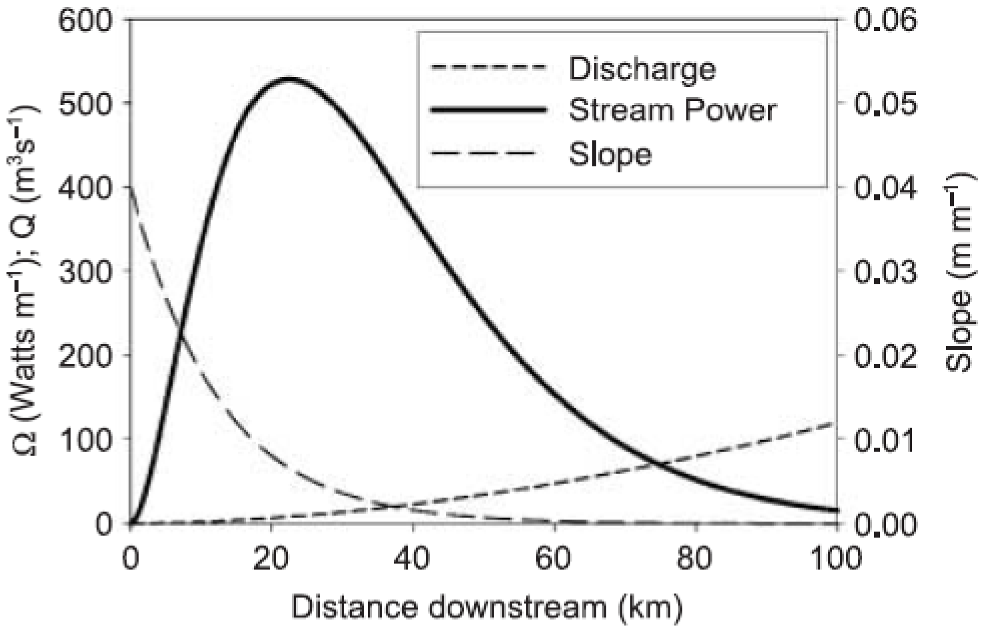


Figure 5.12. Conceptual generalised downstream stream-power model. Source (Barker et al., 2008).

A number of studies have derived stream power values which align with thresholds of geomorphic processes. Bizzi and Lerner (2015) found reaches with stream power lower than 1650 Wm^{-1} tended to be stable and have limited ability to activate geomorphic processes such as incision. However above this value they found stream power was sufficient to trigger erosion processes, to mobilize sediment, and to activate bank erosion and lateral channel migration. Where a sediment supply deficit existed, they suggested that incison of the river bed could be triggered (Bizzi and Lerner, 2015). Nanson and Croke (1992) found braided channels tend to occur at stream powers around 5000 –10 000 Wm^{-1}. There were no clear links that emerged between channel planform

Some general trends in the relationship between channel morphology and stream power emerge from the results of this study. There was a general trend for high *WD* values and low *R* values to be associated with high stream power values. The Ringarooma River also showed a trend for *WD* values to increase downstream. These results reflect the general longitudinal trends of a laterally unstable, low sinuosity channel increasing with increasing stream power (for given grain size) (Bizzi and Lerner, 2015).

Jain et al. (2008) suggest catchment scale patterns and longitudinal profiles of stream power provide better predictors of thresholds for channel processes. Jain et al (2006) found stream-power distribution to be a combination of patterns at two different scales: a broader pattern at the catchment scale and sub-regional variation along each river. They suggested that stream-power variation in the Hunter River catchment was explained by variability in discharge in upstream regions and by variability in slope in mid-catchment and downstream areas (Jain et al., 2006). The rivers in this study do not seem to follow this general pattern.

The longitudinal stream-power profile of the Pipers River (Figure 5.9.D) illustrates the role of discharge on downstream stream-power trends. The lack of large increases in catchment area (a proxy for discharge) coinciding with peaks in stream-power 10-20 km from source suggest stream-power peaks are the result of large slope values, although the large peak prior to 40 km from source is quite closely aligned with the increase in catchment area (and discharge) due to the confluence with Montgomery Creek (Figure 5.9.D). The Ringarooma and Scamander Rivers follow similar patterns, with quite steep drops in elevation occurring quite close to the source, followed by a relatively gentle change in elevation to the mouth. The general non-uniformity between rivers and departure from theorized models of downstream stream-power variability is likely to be a result of local topographic differences. The three rivers in this study all arise in mountain ranges and fall relatively steeply before travelling a short distances of the coast. The Pipers and Ringarooma River travel over an uplifted plain which has low slope (DPIPWE, 2010).

5.4.5. Conclusion

The methods used in this study proved suitable for investigating downstream trends in stream-power in three north-eastern Tasmanian rivers. Substantial variability in the downstream trends in stream-power was found in the Pipers, Ringarooma and Scamander rivers. These rivers were found to have different longitudinal trends and to deviate from the general stream power trends found elsewhere. There was some evidence of an association between channel morphology and stream power, with high *WD* values/ low *R* values occurring at locations with high stream power.

References

ABRAHAMS, A. D. 1972. Drainage densities and sediment yields in Eastern Australia. *Australian Geographical Studies,* 10**,** 19-41.

AMANTE, C. & EAKINS, B. W. 2009. *ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis.* [Online]. National Geophysical Data Center, NOAA. [Accessed 15 September 2014].

ARCEMENT JR, G. J. & SCHNEIDER, V. R. 1989. Guide for selecting Manning's roughness coefficients for natural channels and flood plains. *US Geological Survey Water-Supply Paper,* 2339.

BAGNOLD, R. 1977. Bed load transport by natural rivers. *Water Resources Research,* 13**,** 303-312.

BARKER, D. M., LAWLER, D. M., KNIGHT, D. W., MORRIS, D. G., DAVIES, H. N. & STEWART, E. J. 2008. Longitudinal distributions of river flood power: the combined automated flood, elevation and stream power (CAFES) methodology. *Earth Surface Processes and Landforms,* 34**,** 280-290.

BARTLETT, G. 2008. Simplified geological surface rocks of Tasmania. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Tasmania_simple_geology_map.png. Accessed 15 October 2015.

BARTLEY, R. & RUTHERFURD, I. 2005. Measuring the reach-scale geomorphic diversity of streams: Application to a stream disturbed by a sediment slug. *River Research and Applications,* 21**,** 39-59.

BENDA, L., POFF, N. L., MILLER, D., DUNNE, T., REEVES, G., PESS, G. & POLLOCK, M. 2004. The network dynamics hypothesis: How channel networks structure riverine habitats. *BioScience,* 54**,** 413-427.

BENT, G. C. & WAITE, A. M. 2013. Equations for Estimating Bankfull Channel Geometry and Discharge for Streams in Massachusetts. U.S. Geological Survey Scientific Investigations

BIZZI, S. & LERNER, D. 2015. The use of stream power as an indicator of channel sensitivity to erosion and deposition processes. *River Research and Applications,* 31, 16-27.

BJERKLIE, D. M., DINGMAN, S. L. & BOLSTER, C. H. 2005. Comparison of constitutive flow resistance equations based on the Manning and Chezy equations applied to natural rivers. *Water Resources Research,* 41**,** 1-7.

BOUWMAN, A., BIERKENS, M. F. P., GRIFFIOEN, J. & HEFTING, M. M. 2013. Nutrient dynamics, transfer and retention along the aquatic continuum from land to ocean: towards integration of ecological and biogeochemical models. *Biogeosciences,* 10**,** 1-22.

BRIERLEY, G. J., COHEN, T., FRYIRS, K. & BROOKS, A. 1999. Post-European changes to the fluvial geomorphology of Bega catchment, Australia: Implications for river ecology. *Freshwater Biology,* 41**,** 839-848.

BRIERLEY, G. J. & FRYIRS, K. A. 2005. *Geomorphology and River Mangement: applications of the river styles framework,* Malden MA, Blackwell Publishing.

BRUSSOCK, P. P., BROWN, A. V. & DIXON, J. C. 1985. Channel Form and Stream Ecosytem Models. *Journal of the American Water Resources Association,* 21**,** 859-866.

CARLSTON, C. W. 1963. Drainage density and streamflow. *Geological Survey Professional Paper.* US Government Printing Office.

CHORLEY, R. J. & KENNEDY, B. A. 1971. *Physical Geography: A systems Approach,* London, Prentice Hall.

CHOW, V. T. 1959. *Open-Channel Hydraulics,* McGraw-Hill Book Co.

CHURCH, M. 2002. Geomorphic thresholds in riverine landscapes. *Freshwater Biology,* 47**,** 541-557.

DAY, D. G. 1983. Drainage density variability and drainage basin outputs. *Journal of Hydrology (NZ),* 22**,** 3-17.

DE ROSE, R. C., STEWARDSON, M. J. & HARMAN, C. 2008. Downstream hydraulic geometry of rivers in Victoria, Australia. *Geomorphology,* 99**,** 302-316.

DINGMAN, S. L. & SHARMA, K. P. 1997. Statistical development and validation of discharge equations for natural channels. *Journal of Hydrology,* 199**,** 13-35.

DOUGLAS, I. 1977. *Humid Landforms,* Canberra, Australian National University Press.

DOYLE, M., SHIELDS, D., BOYD, K., SKIDMORE, P. & DOMINICK, D. 2007. Channel-Forming Discharge Selection in River Restoration Design. *Journal of Hydraulic Engineering,* 133**,** 831-837.

DPIPWE 2005. Conservation of Freshwater Ecosystem Values Project (CFEV) database. Tasmania: Water and Marine Resources Division, Department of Primary Industries, Parks, Water and Environment.

DPIW 2008a. Conservation of Freshwater Ecosystem Values (CFEV) Project Technical Report. Hobart, Tasmania: Conservation of Freshwater Ecosystem Values Program, Department of Primary Industries and Water.

DPIW 2008b. Environmental Flows for the Ringarooma River Water Management Plan. Hobart: Water Assessment Branch, Department of Primary Industries and Water.

DURY, G. H., HAILS, J. R. & ROBBIE, M. B. 1963. Bankfull discharge and the magnitude frequency series. *Australian Journal of Science,* 26**,** 123-124.

FERGUSON, R. 1987. Hydraulic and sedimentary controls of channel pattern. *River channels***,** 129-158.

FERGUSON, R. 2010. Time to abandon the Manning equation? *Earth Surface Processes and Landforms,* 35**,** 1873-1876.

FINLAYSON, D. P. & MONTGOMERY, D. R. 2003. Modeling large-scale fluvial erosion in geographic information systems. *Geomorphology,* 53**,** 147-164.

FRISSELL, C. A., LISS, W. J., WARREN, C. E. & HURLEY, M. D. 1986. A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. *Environmental Management,* 10**,** 199-214.

GABLER, R., PETERSEN, J., TRAPASSO, L. & SACK, D. 2008. *Physical geography,* Belmont, USA., Cengage Learning.

GARDINER, V., GREGORY, K. J. & WALLING, D. E. 1977. Further Notes on the Drainage Density-Basin Area Relationship. *Area,* 9**,** 117-121.

GIPPEL, C. 1985. Changes in stream channel morphology at tributary junctions, Lower Hunter Valley, New South Wales. *Australian Geographical Studies,* 23**,** 291-307.

GORDON, N. D., MCMAHON, T. A., FINLAYSON, B. L., GIPPEL, C. J. & NATHAN, R. J. 2004. *Stream hydrology : an introduction for ecologists* Chichester, West Sussex, Wiley.

GRAF, W. L. 1983. Downstream changes in stream power in the Henry Mountains, Utah. *Annals - Association of American Geographers,* 73**,** 373-387.

GRAHAM, B. 1999. Hydrological Analysis of Rivers in the Pipers Catchment: A Report Forming Part of the Requirements for State of Rivers Reporting. Hobart: Land and Water Management Branch, Resource Management and Conservation Division, Department of Primary Industries, Water and the Environment.

GREGORY, K. J. 1976. Drainage networks and climate. *In:* DERBYSHIRE, E. (ed.) *Geomorphology and Climate.* London: John Wiley and Sons.

GREGORY, K. J. & WALLING, D. E. 1968. The variation of drainage density within a catchment. *Hydrological Sciences Journal,* 13**,** 61-68.

GREGORY, K. J. & WALLING, D. E. 1973. *Drainage basin form and process : a geomorphological approach,* London, Edward Arnold.

HARDY, T., PANJA, P. & MATHIAS, D. 2005. WinXSPRO, A channel cross section analyzer, user's manual, version 3.0. *USDA Forest Service - General Technical Report RMRS-GTR***,** 1-100.

HORTON, R. E. 1945. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. *Geological Society of America Bulletin,* 56**,** 275-370.

INSTITUTION OF ENGINEERS AUSTRALIA 1987. Australian Rainfall and Runoff: A Guide to Flood Estimation. Canberra.

JAIN, V., PRESTON, N., FRYIRS, K. & BRIERLEY, G. 2006. Comparative assessment of three approaches for deriving stream power plots along long profiles in the upper Hunter River catchment, New South Wales, Australia. *Geomorphology,* 74**,** 297-317.

JARRETT, R. D. 1984. Hydraulics of high-gradient streams. *J. HYDRAUL. ENGNG. (ASCE),* 110**,** 1519-1539.

KEMP, J. 2010. Downstream channel changes on a contracting, anabranching river: The Lachlan, southeastern Australia. *Geomorphology,* 121**,** 231-244.

KNIGHTON, A. D. 1987a. Streamflow characteristics of northeastern Tasmania: I. regional flood flows. *Papers & Proceedings - Royal Society of Tasmania,* 121**,** 23-33.

KNIGHTON, A. D. 1987b. Streamflow characteristics of northeastern Tasmania: II. Hydraulic geometry. *Papers & Proceedings - Royal Society of Tasmania,* 121**,** 125-135.

KNIGHTON, A. D. 1999. Downstream variation in stream power. *Geomorphology,* 29**,** 293-306.

KNIGHTON, D. 1998. *Fluvial Forms and Processes: A new perspective,* London, Arnold.

KONDOLF, G. M., MONTGOMERY, D. R., PIEGAY, H. & SCHMITT, L. 2003. Geomorphic classification of rivers and streams. *In:* KONDOLF, G. M. & PIEGAY, H. (eds.) *Tools in Fluvial Geomorphology.* Chichester: John Wiley and Sons.

LAND AND WATER AUSTRALIA 2009. An Australian Handbook of Stream Roughness Coefficients. Canberra.

LEOPOLD, L. B. & MADDOCK, T. 1953. The hydraulic geometry of stream channels and physiographic implications. *U. S. Geological Survey Professional Paper.* Reston, VA, United States (USA).

LÓPEZ, R., BARRAGÁN, J. & COLOMER, M. À. 2007. Flow resistance equations without explicit estimation of the resistance coefficient for coarse-grained rivers. *Journal of Hydrology,* 338**,** 113-121.

METEOROLOGY, B. O. 2012. *Tasmanian Rainfall Totals* [Online]. Available: http://www.bom.gov.au/jsp/awap/rain/index.jsp?colour=colour&time=latest&step=0&map=totals&period=36month&area=ta.

MONTGOMERY, D. R. 1999. Process domains and the river continuum. *JAWRA Journal of the American Water Resources Association,* 35**,** 397-410.

MONTGOMERY, D. R. & BUFFINGTON, J. M. 1997. Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin,* 109**,** 596-611.

NANSON, G. & CROKE, J. 1992. A genetic classification of floodplains. *Geomorphology,* 4(6), 459-486.

NAVRATIL, O., ALBERT, M. B. & BREIL, P. 2010. Test of three methods to detect the overbank flow from water level time-series analysis. *Hydrological Processes,* 24**,** 2452-2464.

NAVRATIL, O., ALBERT, M. B., HÉROUIN, E. & GRESILLON, J. M. 2006. Determination of bankfull discharge magnitude and frequency: comparison of methods on 16 gravel-bed river reaches. *Earth Surface Processes and Landforms,* 31**,** 1345-1363.

ORR, H. G., LARGE, A. R. G., NEWSON, M. D. & WALSH, C. L. 2008. A predictive typology for characterising hydromorphology. *Geomorphology,* 100**,** 32-40.

PAGE, K., READ, A., FRAZIER, P. & MOUNT, N. 2005. The effect of altered flow regime on the frequency and duration of bankfull discharge: Murrumbidgee River, Australia. *River Research and Applications,* 21**,** 567-578.

PALLARD, B., CASTELLARIN, A. & MONTANARI, A. 2009. A look at the links between drainage density and flood statistics. *Hydrology and Earth System Sciences,* 13**,** 1019-1029.

PÉREZ-PEÑA, J. V., AZAÑÓN, J. M., AZOR, A., DELGADO, J. & GONZÁLEZ-LODEIRO, F. 2009. Spatial analysis of stream power using GIS: SLk anomaly maps. *Earth Surface Processes and Landforms,* 34**,** 16-25.

PICKUP, G. & WARNER, R. F. 1976. Effects of hydrologic regime on magnitude and frequency of dominant discharge. *Journal of Hydrology,* 29**,** 51-75.

POST, D. A. & JAKEMAN, A. J. 1999. Predicting the daily streamflow of ungauged catchments in SE Australia by regionalising the parameters of a lumped conceptual rainfall-runoff model. *Ecological Modelling,* 123**,** 91-104.

PROSSER, I. P., HUGHES, A. O. & RUTHERFURD, I. D. 2000. Bank erosion of an incised upland channel by subaerial processes: Tasmania, Australia. *Earth Surface Processes and Landforms,* 25**,** 1085-1101.

REINFELDS, I., COHEN, T., BATTEN, P. & BRIERLEY, G. 2004. Assessment of downstream trends in channel gradient, total and specific stream power: a GIS approach. *Geomorphology,* 60**,** 403-416.

RIGGS, H. C. 1976. Simplified slope-area method for estimating flood discharges in natural channels. *Journal of Research of the Us Geological Survey,* 4**,** 285-291.
RILEY, S. J. 1972. A comparison of morphometric measures of bankfull. *Journal of Hydrology,* 17**,** 23-31.
RUPP, D. E. & SMART, G. M. 2007. Comment on "Flow resistance equations without explicit estimation of the resistance coefficient for coarse-grained rivers" by RaÃºl LÃ³pez, Javier BarragÃ¡n, and M. Ã€ngels Colomer. *Journal of Hydrology,* 346**,** 174-178.
RUSTOMJI, P. 2009. A statistical analysis of flood hydrology and bankfull discharge for the Daly River catchment, Northern Territory, Australia. *Water for a Healthy Country National Research Flagship.* Canberra, Australia: CSIRO.
SCHMITT, L., MAIRE, G., NOBELIS, P. & HUMBERT, J. 2007. Quantitative morphodynamic typology of rivers: a methodological study based on the French Upper Rhine basin. *Earth Surface Processes and Landforms,* 32**,** 1726-1746.
SIMON, A., DICKERSON, W. & HEINS, A. 2004. Suspended-sediment transport rates at the 1.5-year recurrence interval for ecoregions of the United States: transport conditions at the bankfull and effective discharge? *Geomorphology,* 58**,** 243-262.
THOMAS, B. F., VOGEL, R. M., KROLL, C. N. & FAMIGLIETTI, J. S. 2013. Estimation of the base flow recession constant under human interference. *Water Resources Research,* 49**,** 7366-7379.
THOMS, M. C. 2006. Variability in riverine ecosystems. *River Research and Applications,* 22**,** 115-121.
TROCH, F. P., VERHOEST, N., GINESTE, P., PANICONI, C. & MÉROT, P. 2001. Variable source areas, soil moisture and active microwave observations at Zwalmbeek and Coët-Dan. *In:* GRAYSON, R. & GUNTER, B. (eds.) *Spatial Patterns in Catchment Hydrology: Observations and Modelling.* Cambridge University Press.
TUCKER, G. E. & BRAS, R. L. 1998. Hillslope processes, drainage density, and landscape morphology. *Water Resources Research,* 34**,** 2751-2764.
WILKERSON, G. V. 2008. Improved bankfull discharge prediction using 2-year recurrence-period discharge. *Journal of the American Water Resources Association,* 44**,** 243-258.
WILLIAMS, G. P. 1978. Bank-full discharge of rivers. *Water Resour. Res.,* 14**,** 1141-1154.
WOLMAN, M. G. & LEOPOLD, L. B. 1957. River flood plains: some observations on their formation. *US Geological Survey Professional Paper.* Washington.
WOLMAN, M. G. & MILLER, J. P. 1960. Magnitude and frequency of forces in geomorphic processes. *Journal of Geology,* 68**,** 54-74.
WOODYER, K. D. 1968. Bankfull frequency in rivers. *Journal of Hydrology,* 6**,** 114-142.
WRIGHT, C. & KEMP, D. Flow Estimation for Flood Management: Understanding the Uncertainty. 5th Flood Management Conference 2007 Warrnambool.

Chapter 6 A remotely derived typology of north-eastern Tasmanian rivers based on channel cross-sectional morphology

6.1. Introduction

The classification of rivers is undertaken out of a basic desire for description and organisation of the world around us, as well as to improve our understanding of fluvial form and processes, and to make better management decisions (Juracek and Fitzpatrick, 2003). The aim of river classification is to simply and meaningfully order streams into groups to achieve specific objectives, with the ordering either natural - based on a natural clustering of objects with similar characteristics, or special, where arbitrary lines are drawn across a continuum of characteristics (Kondolf, 1995). Quantitative studies of river channel morphology have largely failed to identify natural clustering of stream types, and instead have generally found that channel patterns form a continuum rather than discrete types (Ferguson, 1987, Knighton and Nanson, 1993, Kondolf, 1995, Bledsoe and Watson, 2001). However continuums are generally related to scale, with fuzzy boundaries becoming more distinct at coarser scales. Individual elements delineated at one spatial scale are amalgamated into a single element if observed at a sufficiently coarse spatial scale, and are subdivided into several component elements if observed at a finer spatial scale (Poole, 2002).

Regional scale differences in climate, geology, and topography exert controls upon the general geomorphic processes developed upon a landscape (Montgomery, 1999). Because processes operating at a large scale delimit the types of fluvial features and processes that can occur at smaller scales (Frissell et al., 1986), and in an attempt to make classifications widely applicable without having an unfeasibly large number of classes, most classification schemes adopt a hierarchical structure. Common geomorphological based river classifications include those developed by Rosgen (1994) and Montgomery and Buffington (1997), as well as the River Styles methodology of Brierley and Fryirs (2000), which has been widely used in Australia and elsewhere. In the River Styles framework, river types are differentiated based upon reach-scale assemblages of channel and floodplain geomorphic units that are found in differing valley settings under differing energy conditions (Brierley and Fryirs, 2005).

Although there has in general been a lack of research integration between geomorphology and freshwater ecology (Newson and Large, 2006), an increasing recognition that the geomorphic structure and function of a river provides a physical template upon which biotic relationships along rivers can be analysed (Brierley et al., 1999) has led to an adoption of geomorphological templates for river ecology studies. Early examples such as the river continuum concept of Vannote (Vannote et al., 1980) have been succeeded by other models more closely linking geomorphology and ecology (Newson and Newson, 2000, Benda et al., 2004, Chessman et al., 2006) as well as the field of biogeomorphology, which investigates the mutual interactions and feedbacks between fluvial landforms and biological systems (Corenblit et al., 2007).

More recently, recognition of the general degradation of river health worldwide (Poff et al., 2010) and the increasing pressure on global water resources and the aquatic habitat they support (Vörösmarty et al., 2010) has required the development of models to link hydrological changes to ecological responses. The need to retain 'environmental flows', components of the natural flow regime retained in rivers for environmental purposes is widely recognized as being essential for maintaining freshwater biodiversity and ecosystem processes, and achieving environmentally sustainable water resource management (Brisbane Declaration, 2007, Bobbi et al., 2013). However many of the current approaches for determining environmental flow allocations lack data, transparency, and knowledge about important aspects of the aquatic ecosystem (Hart and Pollino, 2009), and the absence of predictive ecosystem models, based on a scientific understanding of flow–ecosystem response relationships, remains a weakness in Australia's management of its water resources (NWC, 2011). The development of a suitable flow alteration-hydrological response model requires a geomorphic framework (Poff et al., 2010). However well established geomorphological classifications are generally location-specific and demanding in terms of resource and expertise required (Bizzi and Lerner, 2012), and if a regional or national scale approach is to be developed, a repeatable, statistically defensible desktop approach is necessary (Dollar et al., 2006). Fluvial geomorphology's research focus and lack of experience in a regulatory role has resulted in classifications and typologies lacking the ability to combine simplicity and validity, let alone be ecologically meaningful (Newson and Large, 2006), and the application of traditional detailed geomorphological models for regional or national river characterisation, although desirable, is unlikely at present (Bizzi and Lerner, 2012).

In an attempt to address this knowledge gap, the Ecological Limits of Hydrological Alteration (ELOHA) framework (Poff et al., 2010) has promoted a hydromorphological approach. Hydro-morphology may be broadly defined as the hydrological characteristics of rivers together with the physical structure that they create (Boon et al., 2010). The ELOHA model classifies river segments within a region using flow regime types and geomorphic features, and develops flow alteration–ecological response relationships for each river type using a combination of existing hydro-ecological literature, expert knowledge and field studies across gradients of hydrologic alteration (Poff et al., 2010). This approach has also been supported by the European Union's Water Framework and Habitats Directives (WFD), which requires all rivers to be considered in terms of their ecological quality, defined partly in terms of hydromorphology (Newson and Large, 2006). The morphological component of hydromorphological classifications has varied between studies. Common classification criteria include channel geometry (planform and channel form), channel substrate, channel bank composition, and valley constriction (Raven et al., 2002, Sipek et al., 2009, Vaughan et al., 2009, Barnes et al., 2013, Rinaldi et al., 2013), and a number of hydromorphological typologies have used stream-power as a classification criteria (Schmitt et al., 2007, Orr et al., 2008, Bizzi and Lerner, 2012).

The development of models to assess the links between flow alteration and hydrological response and assess the health of rivers in Tasmania has seen two approaches to river classification. Most of the river classifications, river assessments and river plans that have been produced for sections of north-eastern Tasmanian rivers have used a detailed reach based model. A number of these have been based upon the nested hierarchical River Styles classification system (Brierley and Fryirs, 2000), which has also been used for the development of the fluvial geomorphological mosaics of the Tas Wide Styles (Jerie et al., 2003), and the Tasmanian River Condition Index (TRCI) (South, 2009). However the wide variety of channel and floodplain forms in Tasmania (Cohen and Household, 2005) has resulted in a large number of classes being developed using these models (13 different TasWide styles are identified for the 28 sites used in this study alone). In addition, the requirements for expert analysis and data collection across a number of scales make these methods relatively resource intensive. The lack of resources, in conjunction with the considerable gaps of knowledge about the hydrologic, geomorphic, and ecosystem interactions at both reach and catchment scales in Tasmania (Resource Planning and

Development Commission, 2003), makes the development of flow alteration – ecological response models for all Tasmanian rivers impractical at present.

The second approach to river classification in Tasmanian has seen the development of a very broad two-classed model based upon the hydrological variability of river discharge (DPIPWE, 2010). Low variability (LV) rivers tend to have higher and more consistent baseflows than high variability (HV) rivers, a lower magnitude of difference between high flow events and mean flows and no cease-to-flow periods (DPIPWE, 2010, Hardie et al., 2012). Geomorphic surveys have revealed clear separations between the two river types, with low variability rivers having a more defined and incised channel and well-sorted sediment structure which is frequently mobilised (DPIPWE, 2010). The classification of catchments provided by this method is then used in conjunction with flow alteration-ecological response studies of 'representative reaches' within each catchment to develop catchment based environmental flow regimes (DPIW, 2007). This objective and quantitative hydrological classification requires few resources, however the wide variety of channel forms and river types included within each of the two classes means that only the most generalised models linking hydrology, geomorphology and ecology can be developed. Representative reach studies offer valuable insights into the ecological response to flow alteration but their subjective location and the inability to transfer knowledge from one study site to others has limited the development of predictive ecosystem models to link the physical and ecological responses of north-eastern Tasmanian rivers to altered flows.

The lack of a desktop based objective and quantitative method for classifying rivers based on channel morphology has restricted the development of a broad and meaningful hydromorphological classification that is able to be applied over large areas with minimal resources. The development of a geomorphological typology with a small number of classes would be of significant benefit to river management in north-eastern Tasmania and particularly in developing flow alteration ecological response models for the establishment of environmental flow regimes.

6.1.1. Aims and Approach

This study aimed to identify potential parameters for an objective and quantitative desktop typology of channel morphology of north-eastern Tasmanian rivers, based on the overall hypothesis that catchment scale parameters control reach scale morphology. The approach taken was to use multivariate and univariate statistical techniques including correlation analysis, principle components analysis (PCA), hierarchical cluster analysis and multiple linear regressions to investigate whether combinations of remotely sensed parameters can replicate groupings of sites that are based on a channel morphology typology. Rather than use a-priori grouping of sites, this study identified natural groupings of sites based on similarities and differences in channel morphology parameters. As the analysis used a limited sample of sites that did not attempt to represent the large variability present in north-eastern Tasmania rivers, it should be considered as an exploratory study only.

Three steps were involved in this study:

1. PCA was first used to identify underlying low dimensional representations of the variability in channel morphology parameters, and, in conjunction with hierarchical agglomerative clustering, was used to identify natural groupings of sites based on these new representations of channel morphology variability.

2. The variability in remotely sensed desktop parameters was then investigated to identify the strongest sources of variability within the remote parameters and potential candidate predictors of channel morphology.

3. Combinations of remote parameters were developed that were best able to describe the natural clustering of sites identified through analysis of channel parameters.

6.2. Methods

6.2.1. Data

Cross-sectional channel data from 219 cross-sections across 28 sites (Table 6.1) were obtained from two sources. Survey data from 40 cross-sections located across 14 different sites was obtained for this study by field survey during the period June 2010 to March 2011. At each site (reach), cross sections were located by establishing a line of sight perpendicular to the channel and a tape measure was secured across the channel to measure horizontal distance. Surveys were undertaken using Leica levels, with depth accuracy estimated to be within +/- 0.01 m and horizontal accuracy to be within +/- 0.1 m. Each cross-section was described by at least ten survey points which included the main morphological features of the channel. The number of cross sections at each site varied between 1 and 5 and cross sections were spaced between 10 and 50 m apart. Locations of cross sections were recorded using GPS receivers, and other relevant field information was noted or photographed. All sites were surveyed at low-flow conditions.

A separate dataset consisting of 179 cross sections obtained from 16 sites (two of which were also included in the group above) (Table 6.1) was obtained from the Tasmanian Department of Primary Industries, Parks, Water and the Environment (DPIPWE). Surveys of these cross-sections were carried out between August 2006 and December 2013, with between 6 and 15 cross-sections spaced 15 to 40 m apart undertaken at each reach. Cross-sections targeted a range of channel forms (pool, riffle, run), and included a range of channel types from simple channels to complex channels with features including in-channel benches, overbank terraces and floodchutes (DPIPWE, 2010). Cross-sectional surveys extended from above obvious

Table 6.1. Details of the sites used in this study (*n* = the number of cross-sections from each site).

Site Number	Site Name	*n*	Group
1	Brid River 2.6 km upstream of tidal limit	1	TEST
2	Dans Rivulet upstream of Mathinna Plains Road	6	TEST
3	Dorset River downstream of Deadhorse Hill Bridge	13	TRAIN
4	Elizabeth River at Merton Vale	6	TEST
5	Great Forester River 2 km upstream of Forester Road	5	TEST
6	Great Forester River at Old Waterhouse Road	13	TRAIN
7	Great Forester River at Prosperity Road	11	TRAIN
8	Great Forester River off Goanna Track	3	TEST
9	Isis River at Isis	14	TRAIN
10	Macquarie River at Honeysuckle Road	12	TRAIN
11	Macquarie River upstream of Mt Morriston bridge	8	TEST
12	Nile River at Deddington gauge	1	TEST
13	Nile River at Nile	11	TRAIN
14	North Esk River at Ballroom	4	TEST
15	Pipers River at Collins Road	1	TEST
16	Pipers River at Lewis Road bend	1	TEST
17	Pipers River at Underwood	5	TEST
18	Pipers River below Colgraves Road	3	TEST
19	Ringarooma River at Wetlands	12	TRAIN
20	Ringarooma River at Yeates Property	10	TRAIN
21	Ringarooma River off Maurice Road	15	TRAIN
22	Ringarooma River upstream of Branxholm	15	TRAIN
23	Ringarooma upstream of Bakers Creek	14	TRAIN
24	Scamander River u/s of Scamander water supply intake	4	TEST
25	South Esk River at Malahide	12	TEST
26	South Esk River at Ormley	12	TRAIN
27	St Patricks River above Lookout Creek	2	TEST
28	Third River at Paling Track	5	TEST

bankfull flow levels on one bank to a similar elevation on the opposite river bank but focused on the proportion of the channel at and below the bankfull flow thresholds; therefore, at most sites, surveying of the extended floodplain (if present) was not undertaken. All sites were surveyed at low-flow conditions (DPIPWE, 2010).

All sites were located on largely unmodified alluvial channels, with site selection based on a range of factors. As mentioned above, much of the data was collected for reasons other than this study, accessibility as well as an attempt to provide a range of stream sizes and types and good geographic coverage of the north-eastern Tasmanian region. However the study necessarily uses a sample of the population, and how well the sample represents the entire population of north-eastern Tasmanian alluvial river reaches is unknown. Consequently, the results are specific to the study sites.

The software package Win XSPRO (Grant et al., 1992) was used to plot each cross-section and to model cross-sectional channel parameters at 0.01 m increments in stage from the deepest point of the channel to well above the maximum elevation of the lowest channel bank of the survey. Plots were modified in some instances by removing features such as floodchutes to ensure that only a single channel was considered at each increment. All statistical analyses were undertaken using the statistical software package R (version 2.12.0).

The data set was separated into two groups for cross validation. The training group (TRAIN) consisted of 164 cross sections from 13 sites (Table 6.1). The second group (TEST) consisted of 58 cross sections from 15 sites and was used as a validation or testing group. Sites were chosen for either TRAIN or TEST group based on the quality of the data (e.g. the number of cross sections). Increasing the number of cross-sections can reduce parameter variability associated with selection of cross-section location and any random measurement error (Stewardson, 2005). The TRAIN group were those sites which had a larger number of cross-sections (10 - 15) than the TEST sites, which each had 8 or fewer cross-sections surveyed.

6.2.2. Parameters

Data from a range of parameters operating at different scales were used in this study. The studied parameters were also broken into two groups: the first group, named channel parameters, contained measurements of channel morphology derived from plotted cross-sections of field surveys (depth, width, wetted perimeter and cross-sectional area) as well as two parameters derived from, and describing, channel morphology: hydraulic radius and width-to-depth ratio (Table 6.2). The second group, named remote parameters, contained parameters that were determined through GIS analysis of the CFEV dataset (catchment area, elevation, slope), or were derived from the CFEV dataset (sub-catchment drainage density, specific stream-power) (Table 6.2).

Table 6.2. Details of both channel and remote study parameters. (Survey = channel cross-sectional survey, CFEV = Conservation of Freshwater Ecosystem Values database (DPIPWE, 2005)).

Parameter	**Symbol**	**Units**	**Source**
Channel Parameters			
Depth	*D*	m	Survey
Width	*W*	m	Survey
Cross-sectional area	*A*	m^2	Survey
Wetted perimeter	*P*	m	Survey
Hydraulic radius	*R*	m	Derived
Width-to-depth ratio	*WD*	-	Derived
Remote Parameters			
Catchment Area	A_d	km^2	CFEV
Drainage density	D_d	km/km^2	Derived
Specific stream-power			Derived
Slope	*S*		CFEV
Elevation	*E*	m	CFEV
Stream Order	SO		CFEV

6.2.2.1. Channel parameters

The bankfull channel cross sectional parameters of depth (*D*), cross sectional area (*A*), wetted perimeter (*P*) and width (*W*) were obtained through analysis of plotted channel cross-sections obtained through field surveys. The software package Win XSPRO (Grant et al., 1992) was used to plot each cross-section and to model cross-sectional channel parameters of *D*, *A*, *P* and *W* at 0.01 m increments in stage. Bankfull stage was estimated at each cross-section by interpretation of the plotted channel profiles, in conjunction with field observations and notes where available. In addition, the minimum of the channel width-to-depth ratio and peaks in the bench index (Riley, 1972) were used to delineate the approximate location of bankfull stage (see Chapter 3). Depth in this study refers to the depth of the bankfull channel at the deepest point or thalweg, not mean cross-sectional depth.

The hydraulic radius (*R*) is a measure of the wetted perimeter in comparison to the cross-sectional area determined by the equation:

$$R = \frac{A}{P} \tag{6.1}$$

High values of R indicate a small wetted perimeter in comparison to the cross-sectional area. More complex channels will have lower R values than simple channels due to a larger wetted perimeter. The hydraulic radius is a measure of the flow efficiency of a channel that has been used in the Manning Equation and other discharge estimation equations (Dingman and Sharma, 1997). The hydraulic radius of the bankfull channel (R) at each cross-section was defined using equation 6.1 and the bankfull channel parameters A and P derived from the plotted cross-sections.

The width-to-depth ratio (WD) has been extensively used as a measure of channel shape and has also been found to be a determinant of channel planform (Li et al., 2013). High WD values suggest wide shallow channels, while low WD values indicate deeper narrower river channels. In this study, WD refers to the width-to-depth ratio of the bankfull channel at each cross-section as determined by dividing the bankfull channel width (W) by the mean bankfull channel depth (where the mean depth = A / W)) to arrive at the equation:

$$WD = \frac{W^2}{A} \tag{6.2}$$

6.2.2.2. Remote parameters

The values of the parameters of catchment area (A_d), maximum elevation (E) and slope (S) were obtained for each site using a Geographic Information System (GIS) (Arc Map 7.2) to interrogate the Tasmanian Conservation of Freshwater Ecosystem Values (CFEV) data set (DPIPWE, 2005). This dataset is based on a 1:25 000 drainage network data layer and a 25 m digital elevation model (DEM) (DPIW, 2008). CFEV defines a reach or river link as a section of river between confluences, and this approach is adopted in this study (DPIW, 2008).

Catchment area is the total area upstream that drains into a site. Catchment area is correlated with most catchment characteristics (Haddad and Rahman, 2011), and stream width, mean annual discharge and the extent of riparian vegetation at a site generally scale directly with the catchment area of that site (Leopold et al., 1964). Elevation is a variable that represents local environmental conditions (Altermatt et al., 2013), and can reflect the influence of climate, topography, vegetation and lithology. Both catchment area and elevation values for each site in this study were determined from the CFEV dataset using ARC GIS, being the accumulated catchment area and maximum elevation of the upper end of the stream link (reach or segment) upon which the site was located. The maximum elevation of a river section is calculated from the grid cell of the DEM which coincided with the most upstream end of the river section (DPIW, 2008).

The influence of channel gradient (slope) on channel morphology has been a focus for research (Schumm and Khan, 1972) and changes in slope have been used to delineate macro-reaches from longitudinal profile data (Dollar et al., 2006). Unlike geometric cross sectional variables which are precisely defined, channel slope is difficult to define in a quantitative manner (Gippel, 1985), and a wide range of definitions and measurement techniques appear in the literature. This study used CFEV reach slope values, which were derived from the 25 m DEM. As slopes tend to decrease with increasing grid size, the scale of the grid has been found to have an effect on slope data (Finlayson and Montgomery, 2003). However Reinfelds et al. (2004) found good agreement between 25 m x 25 m cell DEM derived gradients and those determined in the field on river reaches in coastal New South Wales. CFEV slope values have also been found to generally be in close agreement with field derived values in other studies (DPIPWE, 2010). Sites with a recorded slope value of zero in the dataset were assigned an S value of 0.0001 to simplify the analysis.

Drainage density (D_d), the ratio of stream length to catchment area, is expressed by:

$$D_d = \frac{\sum L}{A_d} \tag{6.3}$$

Where ΣL is the total length of streams within a catchment and *Ad* is the drainage area of the catchment, both in units of the same system (Horton, 1945). Drainage density reflects the climate patterns, geology, soils and vegetation cover of a catchment (Gordon et al., 2004). Drainage density values for each site were determined as the value for the CFEV sub-catchment within which the site was contained (See Chapter 5.2).

Stream power (Ω) is the product of water density, flow rate and water surface slope (Bagnold, 1977), determined using the equation

$$\Omega = \rho g Q_{bf} S \tag{6.4}$$

Where ρ is water density, g is the force of gravity, Q_{bf} the theoretical bankfull discharge, S is the mean slope of water (substituted in this study with mean reach slope) and W is the bankfull width (Leopold et al., 1964). Stream power has been shown to have an important influence on many aspects of the fluvial system: channel form characteristics such as bedform type, channel pattern, bedload transport rates, the geomorphic effectiveness of flood discharges (Knighton, 1999a), and has been the focus of a number of studies (Montgomery and Buffington, 1997, Knighton, 1999a, Reinfelds et al., 2004, Schmitt et al., 2007, Orr et al., 2008). Q_{bf} from Equation 6.4 was necessarily estimated for each site in this study. The flood with the two year average return interval (Q_2) was assumed to be equivalent to Q_{bf} (see Chapter 5.3), and from the power-law equations between discharge and catchment area developed in Chapter 4 was estimated by:

$$Q_b = A_d^{0.9} \tag{6.5}$$

Using this method to determine stream-power values results in tributary junctions corresponding to significant changes in downstream variation of stream power (Knighton, 1999b, Jain et al., 2006). As stream-power is a remotely derived parameter that has been used previously in the development of hydromorphological classifications (Orr et al., 2008), it was seen as a strong potential candidate for a predictor variable

6.2.3. Multivariate Statistical Methods

6.2.3.1. Principle Component Analysis

Principle Component Analysis (PCA) is a multivariate statistical technique used to find underlying relationships between variables within a dataset (Wold et al., 1987). PCA works by combining variables to form a set of new orthogonal variables, known as principle components, which describe underlying processes in a larger dataset of inter-correlated quantitative dependent variables (Gordon et al., 2004). Observations with high contributions and different signs represent the two endpoints of each component (Abdi and Williams, 2010). PCA is commonly used for data reduction, simplification and classification and can be used in combination with other techniques to build models of how physical systems behave (Wold et al., 1987). PCA has previously been used to build models linking stream geomorphic condition to fish community characteristics (Sullivan et al., 2006) and Schmitt et al. (2007) used PCA in conjunction with other techniques to develop a hydromorphological typology of rivers based on remotely sensed variables. Hughes (1987) used PCA to develop a hydrological classification of Tasmania. PCA also represents patterns of similarity in the observations and the variables by displaying them as points in maps (Abdi and Williams, 2010).

PCA has been criticised because the principal components, which are linear combinations of the original variables, are scale dependent, with the highest variance amongst the dataset dominating the first component of the PCA (Gordon et al., 2004). However applying variance scaling to the dataset prior to analysis largely removes this problem (Wold et al., 1987). Other criticisms relate to the lack of objective measures to test the results of the PCA (Gordon et al., 2004), which in this study has been overcome by the use of cross-validation methods to validate the results.

In this study PCA was conducted using the ‘prcomp’ function of the package in R, which uses a singular value decomposition of the centered and scaled data matrix, rather than using eigen on the covariance matrix. Data was scaled prior to analysis by dividing each column of data by its standard deviation (Becker et al., 1988). The number of principle components retained in each PCA was determined using Kaiser's criterion (keeping components with a variance greater than 1) (Jolliffe, 1973) and through examination of ‘scree’ plots (Abdi and Williams, 2010).

6.2.3.2. Hierarchical agglomerative clustering

Cluster analysis was used in an attempt to identify natural grouping or clustering of sites. Clustering is a generic term for the common statistical technique of grouping a set of objects such that objects in the same group are more similar, in some sense, to each other than to those in other groups. There are many different clustering algorithms and techniques available. Because the number of clusters (groups) was not known a priori in this study, hierarchical cluster analysis was used. Hierarchical agglomerative clustering is used to explore similarities and differences between observations and factors (Kaufman and Rousseeuw, 2005) Agglomerative clustering has been used in a wide range of environmental studies including grouping water quality samples (Kovács et al., 2014) river valley segment delineation from GIS databases (Brenden et al., 2008) and to develop a classification of estuaries (Engle et al., 2007). Hierarchical clustering starts with each observation being considered a small cluster, and at each sequential stage the two ‘nearest’ clusters are merged to form a larger cluster until only one large cluster remains which contains all the observations (Maechler et al., 2014). Methods of determining the nearest cluster vary, and in this study a standard or 'average' method was used where the distance between two clusters is the average of the dissimilarities between the points in one cluster and the points in the other cluster (Kaufman and Rousseeuw, 2005). A clustering dendogram was produced for each combination of factors at each stage of the analysis (Maechler et al., 2014). Following common procedure (Kaufman and Rousseeuw, 1990), data were standardised prior to analysis by subtracting the median and dividing by the mean average deviation, and a distance or dissimilarity matrix was created which contained the pairwise distances between points. This study used Manhattan distances, which are the sum of absolute differences between points (Gower, 1971). Manhattan distances are recommended for heterogeneous data as this distance decomposes into contributions made by each variable (Kaufman and Rousseeuw, 1990).

6.3. Results and Discussion

6.3.1. Analysis of channel cross-sectional parameters

The variability in channel morphology parameters was examined using a number of methods. The variability in the distribution of the observed values of the channel morphology parameters depth (*D*), cross-sectional area (*A*), wetted perimeter (*P*), width (*W*), hydraulic radius (*R*) and width-to-depth ratio (*WD*) along each of the 13 reaches (sites) was examined using probability density plots (Appendix 6.1). Density estimates used a Gaussian function for smoothing kernels (Hothorn, 2009) with the bandwidth set at 0.9 times the minimum of the standard deviation (Silverman, 1986). The distribution of channel parameter values along each reach were highly variable. Few parameters followed a normal distribution, with most heavily skewed and some being multi-modal (Appendix 6.1).

Plots of mean site values of *D, A, P, W, R* and *WD* with +/- 95% confidence intervals were also produced, and are shown in Appendix 6.2. Confidence intervals were estimated by bootstrapping samples, with 1000 iterations (DiCiccio and Efron, 1996). The distribution of both the mean values and 95% confidence intervals also showed a great deal of variation, reflecting the wide range of catchment areas and climatic, lithologic and geomorphological settings in the region within which the sites were located.

A summary of channel morphology parameters *D*, *A*, *P*, *W*, *R* and *WD* from the 164 cross-sections located across the 13 sites designated TRAIN group is shown in Table 6.3. The number of cross-sections at each site ranged from 10 cross-sections at site 20 to 15 cross-sections at sites 21 and 22. The mean number of cross sections across the 13 sites was 12. Mean site *D* ranged from 1.04 to 3.63 m, with the associated *CV* for mean *D* ranging from 0.07 to 0.32, with an average *CV* of 0.21. Mean site *A* ranged from 7.31 to 64.13 m^2, while the *CV* for mean site *A* ranged from 0.16 to 0.47, with the mean being 0.31. Mean site *P* for the 13 sites ranged from 13.87 to 34.60, while *CV* for *P* ranged from 0.08 to 0.34, with a mean of 0.18. Mean *W* for each ranged from 13.87 to 33.42 m and the associated *CV* ranged from 0.09 to 0.35 with an average *CV* of 0.19. Mean R ranged from 0.20 to 2.11 m while *CV* ranged from 0.10 to 0.49 with an average *CV* of 0.25. Mean *WD* ranged from 11.61 to 85.44, while *CV* for *WD* ranged from 0.14 to 0.66 with an average *CV* of 0.36 (Table 6.3).

The range of mean channel parameter values for *D*, *P*, *A* and *W* reflects the range of catchment areas found across the 13 study sites, with each parameter generally increasing as catchment area increased (Table 6.3). Mean hydraulic radius (*R*) also generally increased with increasing catchment area. There was no correlation between *WD* values and catchment area. The maximum *CV* that occurred within a site for the parameter *D* occurred at site 10, while the maximum *CV* for *A*, *P, W* and *R* occurred at site 9, and the maximum within site *CV* for *WD* occurred at site 7 (Table 6.3). There was no correlation between the number of cross sections at a site and *CV* values. The *CV* of combined mean site values of each parameter are also shown in Table 6.3. The *CV* between mean site values was larger than the average within site *CV* for all parameters, although there was little difference between the average within site *CV* for *WD* and the *CV* between mean site *WD*. However the maximum within site *CV* for parameters *P, W* and *WD* was higher than the between site *CV*.

To examine the distribution of channel parameter values of the 164 cross-sections of the 13 TRAIN sites and the relationships between the parameters, a scatterplot matrix was produced with histograms of each channel morphology parameter and scatterplots relating each parameter to each other parameter (Figure 6.1). Correlations between parameters were also quantified, with linear (Pearson) correlation coefficients between the channel parameters shown in Table 6.4. The distribution of all channel parameters were right skewed to varying degrees (Figure 6.1), and as expected there was significant correlation between a number of channel parameters.

Table 6.3. Summary of channel morphology parameters for 13 TRAIN sites (*n* = number of cross-sections, *CV* = coefficient of variation, *D* = depth, *A* = channel cross-sectional area, *P* = wetted perimeter, *W* = width, *R* = hydraulic radius and *WD* = width-to-depth ratio).

Site	*n*	*D* (m)		*A* (m^2)		*P* (m)		*W* (m)		*R* (m)		*WD*	
		Mean	***CV***	**Mean**	***CV***	**Mean**	***CV***	**Mean**	***CV***	**Mean**	***CV***	**Mean**	***CV***
3	13	1.36	0.22	18.38	0.22	23.15	0.12	22.28	0.13	0.80	0.21	29.09	0.29
6	13	1.99	0.21	22.74	0.36	19.12	0.19	17.28	0.18	1.17	0.18	13.64	0.18
7	11	1.32	0.30	13.50	0.29	16.23	0.20	15.42	0.21	0.85	0.23	18.98	0.51
9	14	1.04	0.29	7.31	0.47	14.38	0.34	13.87	0.35	0.51	0.28	28.62	0.48
10	12	1.20	0.32	10.99	0.46	15.80	0.26	15.18	0.27	0.68	0.39	24.66	0.42
13	11	2.54	0.18	30.15	0.17	21.40	0.15	19.21	0.16	1.42	0.15	12.57	0.29
19	12	1.86	0.14	36.55	0.19	34.60	0.15	33.42	0.15	1.07	0.18	31.70	0.33
20	10	1.36	0.19	22.55	0.21	21.64	0.08	20.34	0.09	1.04	0.20	19.15	0.26
21	15	1.05	0.19	10.68	0.43	14.59	0.20	13.95	0.20	0.71	0.23	19.21	0.21
22	15	1.40	0.28	26.19	0.46	27.50	0.21	26.86	0.21	0.92	0.31	30.58	0.29
23	14	1.15	0.18	19.73	0.40	27.72	0.09	27.08	0.09	0.70	0.33	40.75	0.24
25	12	2.61	0.10	50.11	0.16	29.08	0.08	27.70	0.09	1.72	0.11	15.49	0.14
26	12	3.63	0.07	64.13	0.25	30.77	0.29	27.10	0.32	2.11	0.10	11.61	0.43
Mean	12		0.21		0.31		0.18		0.19		0.25		0.36
CV of mean site values			0.45		0.64		0.29		0.30		0.43		0.39

The strongest linear correlations were between *P* and *W* (0.992), between *D* and *R* (0.928), between *A* and *R* (0.890), and between *D* and *A* (0.862), all with *p* values < 0.005 (Table 6.4).

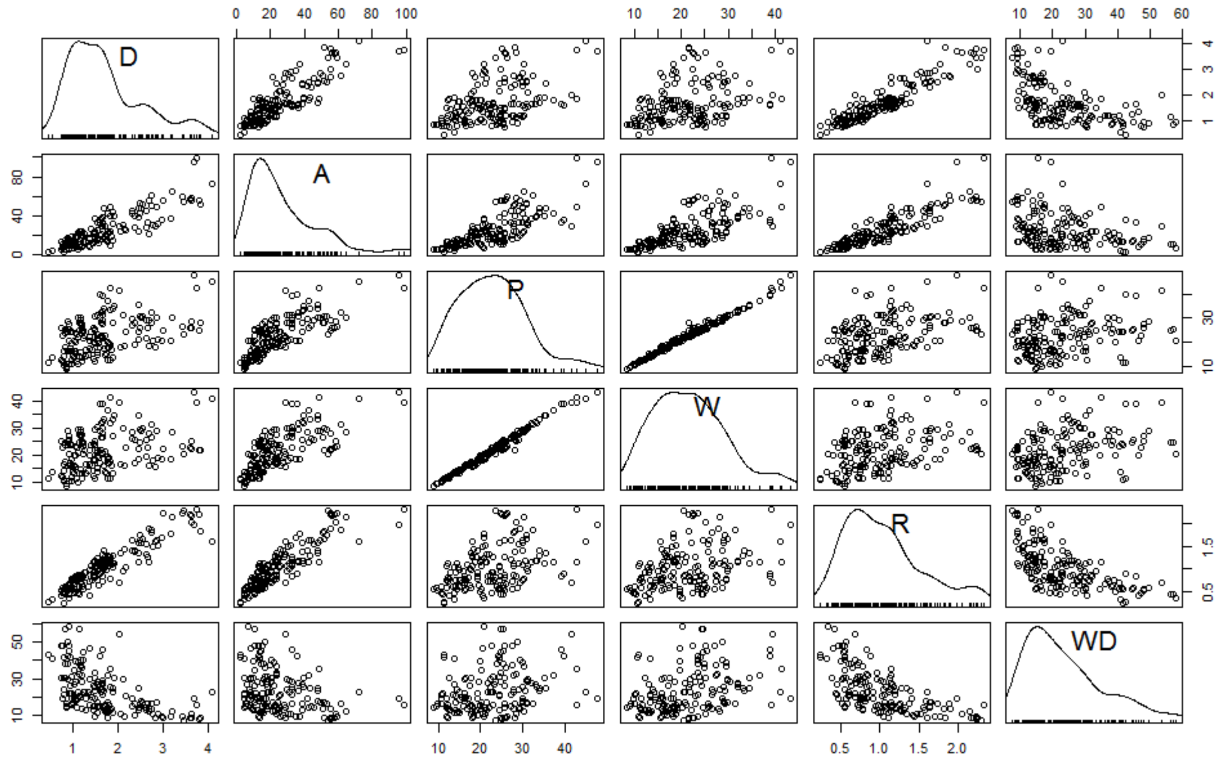


Figure 6.1. Scatterplots and histograms (centre diagonal plots) of channel morphology parameters from 164 cross-sections from 13 TRAIN sites (*D* = depth, *A* = cross-sectional area, *P* = wetted perimeter, *W* = channel width, *R* = hydraulic radius and *WD* = width-to-depth ratio).

Table 6.4. Linear (Pearson) correlation coefficients for channel morphology parameters based on 164 cross-sections from 13 TRAIN sites. (df = 162, all correlations have *p* values < 0.005; *D* = depth, *A* = cross-sectional area, *P* = wetted perimeter, *W* = channel width, *R* = hydraulic radius and *WD* = width-to-depth ratio).

Parameter	*A*	*P*	*W*	*R*	*WD*
D	0.862	0.471	0.375	0.928	-0.548
A		0.759	0.696	0.890	-0.323
P			0.992	0.446	0.273
W				0.363	0.349
R					-0.639

A PCA was conducted to identify underlying low dimensional uncorrelated sources of variability in the highly correlated (Table 6.4) dataset of cross-sectional channel parameters from the TRAIN sites. The first component (PC1) of PCA1 explained more than 63% of the variance, while the first two components of PCA1 combined explained in excess of 95% of the variance in the dataset (Table 6.5). Due to being orthogonal to each other, the composition of each of the first two components of PCA1 was quite different, with the parameters *D*, *A*, *R* and *WD* operating in different directions in each component, and only *P* and *WD* operating in the same direction in each component (Table 6.6). The unchanging status of *P* and *W* in relation to both the first and second components (PC1 and PC2) of PCA1 can be seen in Figure 6.2, where the parameters *WD*, *A*, *D* and *R* run in an orthogonal direction to *W* and *P*. The strong correlations that were found between channel parameters *P* and *WD* and between *R* and *D* (Table 6.6) can also be seen in Figure 6.2.

Table 6.5. Standard deviation and variance of the principle components (PC1 – PC6) of the principle components analysis (PCA1) based on the parameters depth (*D*), cross-sectional area (*A*), wetted perimeter (*W*), hydraulic radius (*R*) and width-to-depth ratio (*WD*) from 164 cross-sections comprising the TRAIN group.

	PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
Standard Deviation	1.951	1.395	0.399	0.247	0.167	0.043
Proportion of Variance	0.634	0.324	0.027	0.010	0.005	0.000
Cumulative Variance	0.634	0.958	0.985	0.995	1.000	1.000

Table 6.6. Composition of the first two principal components (PC1 and PC2) of PCA1 based on the channel parameters depth (*D*), cross-sectional area (*A*), wetted perimeter (*P*), width (*W*) hydraulic radius (*R*) and width-to-depth ratio (*WD*) from 164 cross-sections comprising the TRAIN group.

	D	***A***	***P***	***W***	***R***	***WD***
PC1	0.457	0.505	0.400	0.367	0.461	-0.168
PC2	-0.248	-0.003	0.441	0.491	-0.288	0.648

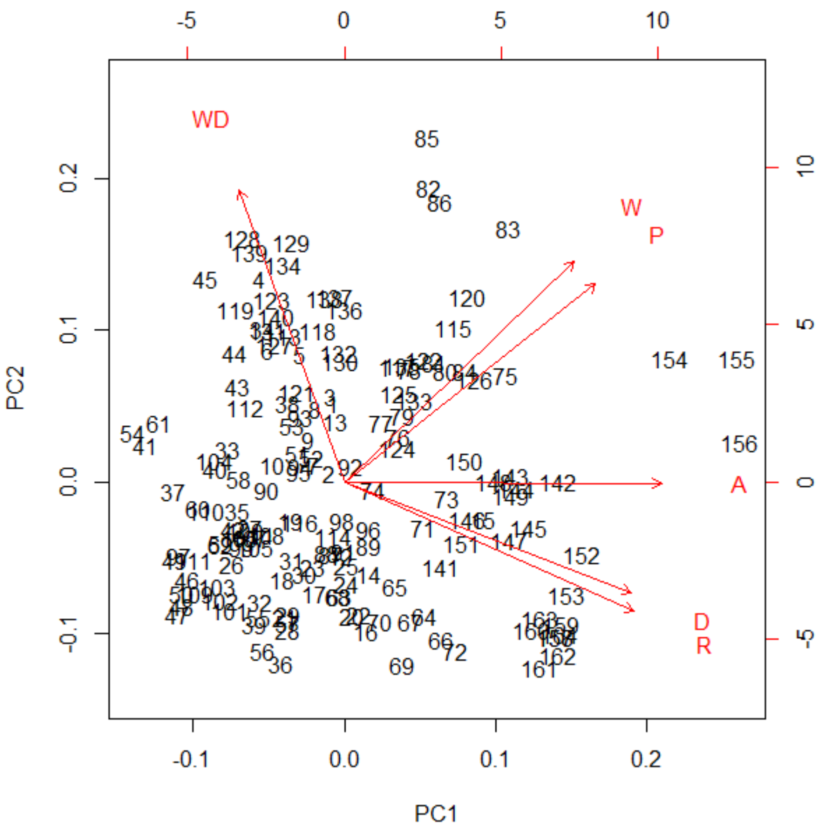


Figure 6.2. Biplot approximating the distribution of values from 164 cross-sections comprising the TRAIN group against the first and second principle components (PC1and PC2) of PCA1. The channel parameters depth (*D*), cross-sectional area (*A*), wetted perimeter (*P*), width (*W*), hydraulic radius (*R*) and width-to-depth ratio (*WD*) are represented as linear axes against the observation loadings.

A number of transformations of the data were investigated to reduce the skew in channel parameters (Appendix 6.1). Both the natural logarithm and a weighting based on estimated discharge (Section 5.3) were trialled on the cross-sectional values of the channel parameters *D*, *A*, *P* and *W*. However, these transformations were found to reduce the variability in orthogonal components derived from the dataset and analysis on the transformed data may not reflect the underlying phenomena. As scaleless parameters, no transformations were trialled on *R* or *WD*. Based on the results of the correlation analyses (Figure 6.1 and Table 6.5), and PCA1 (Tables 6.5 and 6.6 and Figure 6.2), the channel parameters *D*, *A* and *W* were removed and a second principle component analysis (PCA2) was undertaken on the 164 observations (cross-sectional values) using the remaining channel parameters *P*, *R* and *WD*. Normally at least four variables should be retained for principal component analysis (Jolliffe, 1973), however the PCA was undertaken on three variables in this instance as the purpose of the analysis was exploratory only. The standard deviation and variance of each principle component of PCA1 is shown in Table 6.7, the composition of the first two components of PCA2 are shown in Table 6.8, and a plot of the 164 observations against the first two components of PCA2 is shown in Figure 6.3.

Table 6.7. Standard deviation and variance of first three principle components (PC1, PC2 and PC3) of the principle components analysis (PCA2) on 164 individual cross sections from TRAIN group using the three channel parameters wetted perimeter (*P*), hydraulic radius (*R*) and width-to-depth ratio (*WD*).

	PC1	**PC2**	**PC3**
Standard Deviation	1.293	1.119	0.279
Proportion of Variance	0.557	0.413	0.025
Cumulative Variance	0.557	0.974	1.000

Table 6.8. Composition of the first two principal components (PC1 and PC2) of PCA1 on values of wetted perimeter (*P*), hydraulic radius (*R*) and width-to-depth ratio (*WD*) from 164 cross-sections from the 13 sites comprising the TRAIN group.

	P	***R***	***WD***
PC1	-0.249	-0.750	0.613
PC2	0.838	0.151	0.525

The first component (PC1) of PCA2 explained more than 55% of the variance, while the first two components of PCA1 combined explained in excess of 97% of the variance in the dataset (Table 6.7).

The first principal component (PC1) of PCA1 represented a contrast between strong negative values of *R* and strong positive values of *WD*, along with a smaller negative *P* component, while the second component (PC2) had a very strong *P* component in conjunction with a significant positive *WD* component (Table 6.8). Cross-sections with large values of PC1 are thus likely to have small *R* values, suggesting a small cross-sectional area in relation to the size of the wetted perimeter, and large *WD* values, suggesting wider and shallower channels than those which have small values of PC1. Conversely, cross-sections which have small PC1 values tend to have large *R* values, which may indicate channels with relatively small wetted perimeters in comparison to their cross-sectional area, and small *WD* values, which suggests channels that are relatively deep in comparison to their width. Cross-sections which have high values of PC2 are likely to be those with large *P* and relatively large *WD* values, suggesting these cross-sections tend to be wider than other sites, and generally shallow.

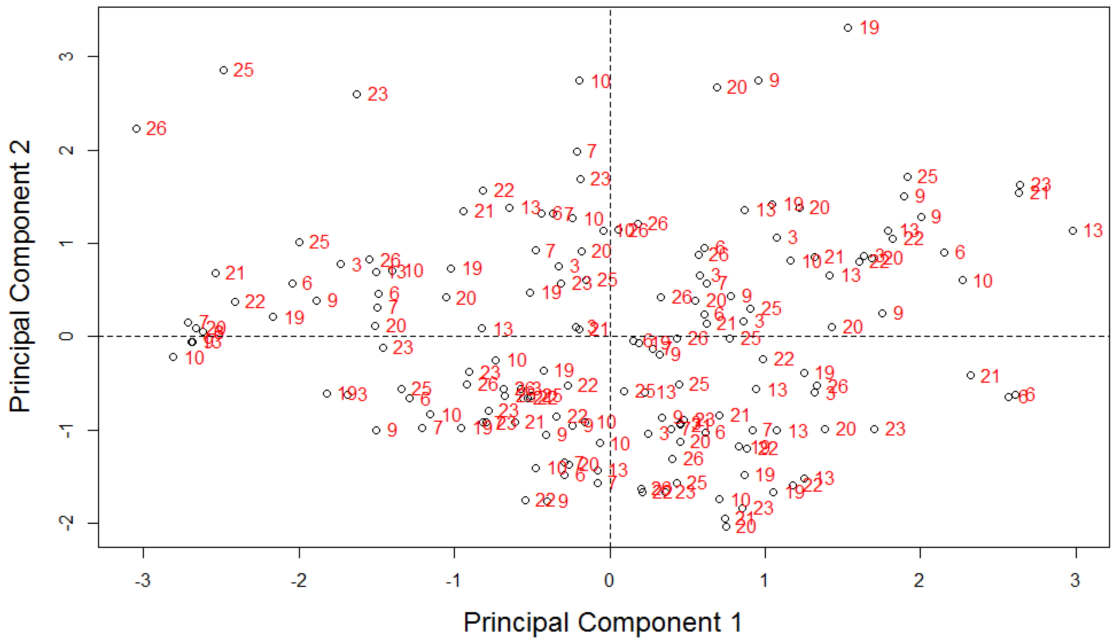


Figure 6.3. Distribution of 164 observations (cross-sections) from TRAIN sites against the first two principle components (PC1 and PC2) of the principal components analysis of the channel parameters P, R and WD (PCA1). Observation labels refer to site number (Table 6.1).

No clustering of cross-sections by site was discernible in the plot of TRAIN cross-sections against the first and second principal components (PC1 and PC2) of PCA2 (Figure 6.3). While cross-sections seemed to be generally scattered across the components, the number of observations (cross-sections) and the possibility of overlapping of groupings made the observation of trends in the dataset difficult. Consequently, in an attempt to identify natural clustering based on the underlying variability in the TRAIN dataset identified by PCA1, a hierarchical agglomerative cluster analysis was undertaken on the 164 cross-sections from the TRAIN group of sites using the loadings of the first and second rotations (PC1 and PC2) of PCA1. The dendogram tree produced by the cluster analysis was cut at 4 groups, and the distribution of each cross-section into those 4 groups is shown in Table 6.9. The majority of sites had all cross-sections (sites 7, 19, 21, 25 and 26) or a large proportion of cross-sections (sites 6, 20, 22 and 23), fall within one group. The remaining sites (sites 3, 9, 10 and 13) still had in excess of 60% of cross-sections fall within one group. Based on the results of the cluster analysis, the sites of the TRAIN group could be divided into three groups. Group 1 contained sites 3, 19, 22, and 23, group 2 contained sites 6, 7, 9, 10, 13, 20 and 21, and group 3 contained sites 25 and 26. No sites had a large number of cross-sections in group 4 (Table 6.9).

Table 6.9. Distribution of 164 channel cross-sections from the 13 TRAIN sites into groups using hierarchical agglomerative clustering of the loadings of PC1 and PC2 from PCA2, which was based on the parameters *P*, *R* and *WD*.

Group	**Site Number**												
	3	6	7	9	10	13	19	20	21	22	23	25	26
1	8	0	1	3	2	2	12	2	0	13	12	0	0
2	5	11	10	9	8	9	0	8	15	2	0	0	0
3	0	1	0	0	0	1	0	0	0	0	0	12	12
4	0	0	0	2	2	0	0	0	0	0	2	0	0

The loadings of the first two principle components from PCA2 were then applied to the standardised mean values of the channel parameters for each of the TRAIN sites, and the results are plotted in Figure 6.4. In this plot, the three groups of sites identified using the hierarchial cluster analysis (Table 6.9) could be observed. Sites 3, 19, 22, and 23 grouped in the upper right quadrant (positive PC1 and PC2 values), group 2 containing sites 6, 7, 9, 10, 13, 20 and 21 fell in the lower half of the plot (negative PC2 values), and group 3 containing sites 25 and 26 was in the upper left quadrant (negative PC1 and positive PC2) (Figure 6.4).

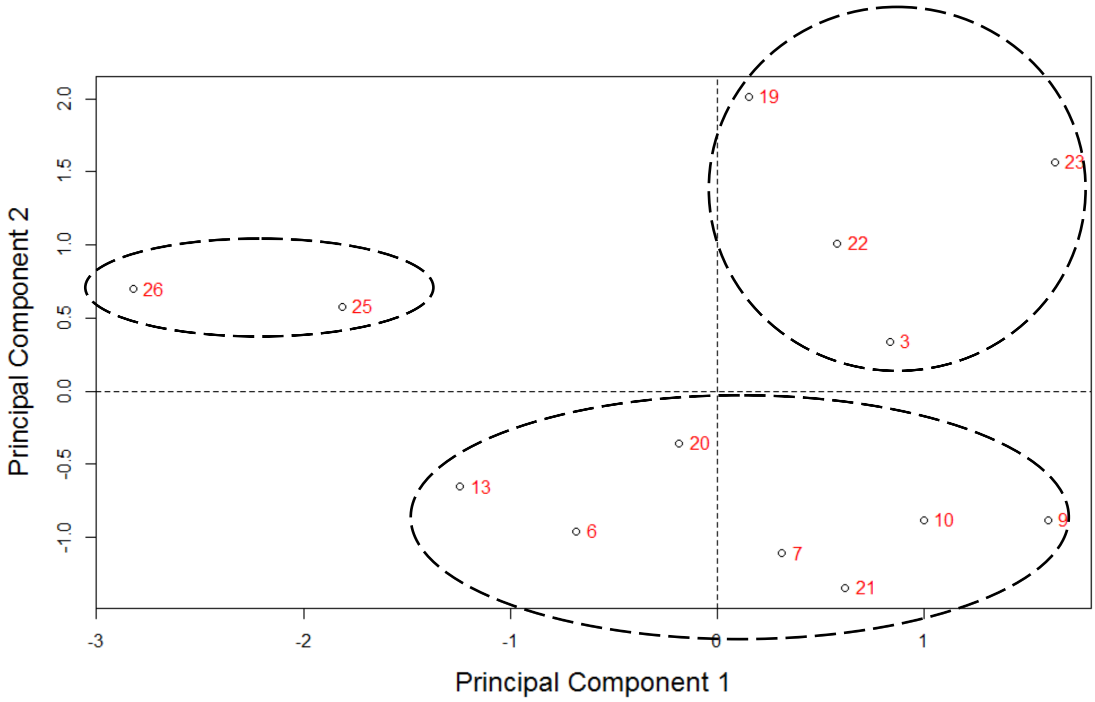


Figure 6.4. Mean site TRAIN values plotted against the first and second principal components (PC1 and PC2) of PCA1 which was based on the parameters P, R, and WD. Circles indicate groupings identified through the analyses.

To ascertain if the observed grouping of TRAIN sites based on the principle components of PCA2 using *P*, *R* and *WD* (Table 6.9 and Figure 6.4) was specific to that dataset or was more generally applicable to Northern Tasmanian rivers, the results were tested on a separate group of sites. Loadings from the first two principle components of PCA2 were applied to the scaled cross-sectional channel parameter values of the TEST sites (Table 6.1). Some grouping of TEST site cross-sections was observed in the plot against PC1 and PC2 of PCA2 (Figure 6.5). Cross-sections from site 28 were closely clustered in the bottom right quadrant of the plot (positive PC1 and negative PC2), while all cross sections from site 24 and a majority from site 11 fell in the upper left quadrant (negative PC1 and positive PC2).

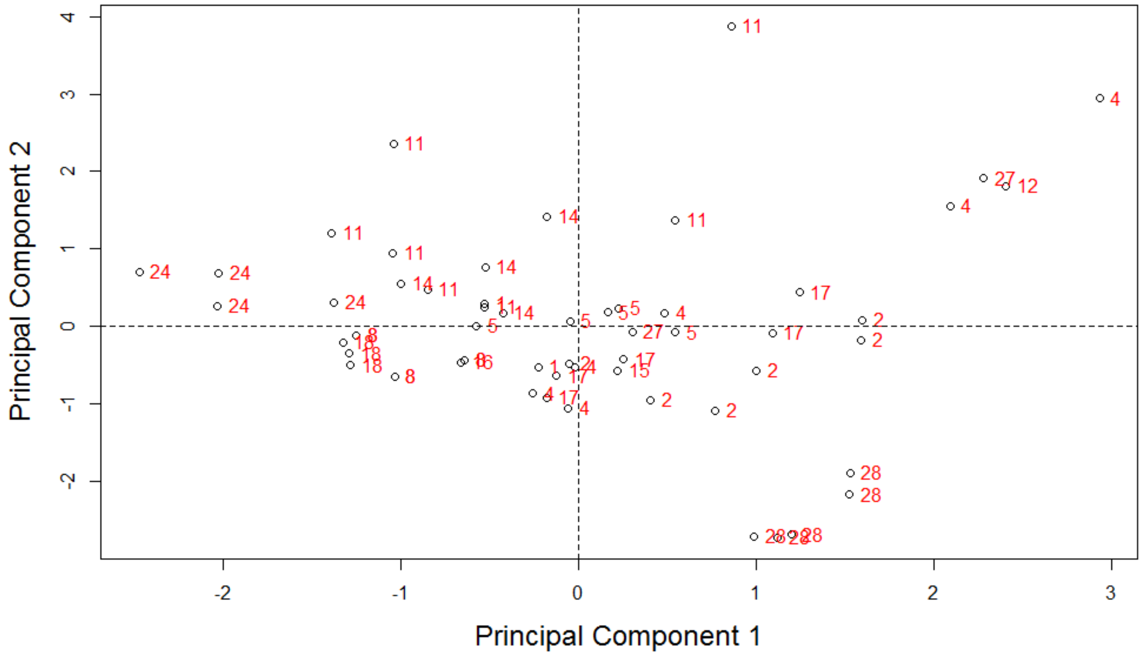


Figure 6.5. Plot of 58 cross-sections from the 15 TEST sites against the first and second principal components (PC1 and PC2) of PCA2 which was based on the channel parameters P, R, and WD.

A hierarchial cluster analysis of the TEST site cross-sections was conducted to identify natural groupings based on cross-sectional channel parameters, and to determine wheter groupings identified in the TRAIN sites would be repeated in the TEST sites. The clustering resulted in the majority of cross-sections falling within a single group (Table 6.10), although only three of the 12 sites with more than one cross-section had all cross-sections fall within one group. Based on where the majority of cross-sections from a site fell, group 1 dominated the clustering and contained sites 1, 2, 4, 5, 6, 11, 14, 15, 16 and 17. Group 3 contained sites 12, 18 and 24, and group 4 contained site 28. Site 27 was evenly distributed between group 1 and group 3, and there were no sites in group 2.

Table 6.10. Hierarchial clustering of the 58 cross-sections from the 15 TEST sites using loadings from the first and second principal components (PC1 and PC2) of PCA2 which was based on the channel parameters *P, R,* and *WD*.

Group	Site Number														
	1	2	4	5	8	11	12	14	15	16	17	18	24	27	28
1	2	6	4	5	6	4	0	3	1	1	5	3	4	1	0
2	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
3	0	0	1	0	0	2	1	1	0	0	0	12	12	1	0
4	0	0	0	2	2	0	0	0	0	0	2	0	0	0	5

The groupings of sites that were identified using the loadings of PC1 and PC2 from PCA2 being applied to the combined 219 TRAIN and TEST site cross-sections is not evident in the plot of mean TRAIN and TEST site values against PC1 and PC2 of PCA2 (Figure 6.6).

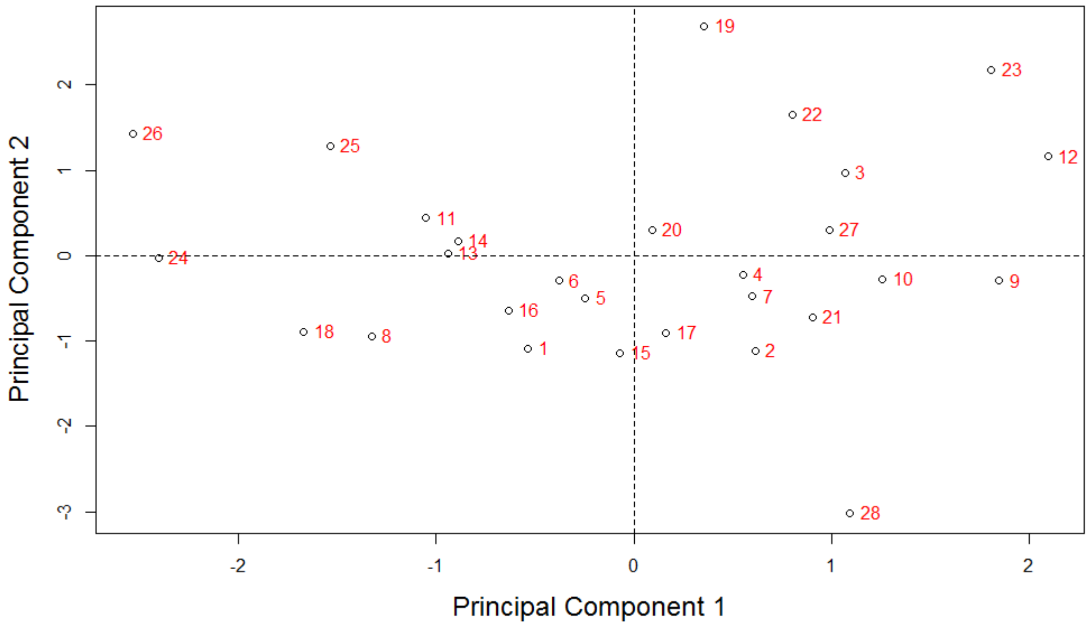


Figure 6.6. Mean values of TRAIN and TEST sites plotted against the first and second principal components (PC1 and PC2) of PCA1 which was based on the parameters *P*, *R*, and *WD*.

In the final stage of the channel parameter analysis, the grouping of sites against a maximised *WD-R* axis was conducted. To enhance the grouping effect identified in PCA2, the *P* component of PC1 from PCA2 was removed and a new *WD-R* axis was created. This new axis was based on a number of trial PCA's using reduced parameters and combinations of observation. The final loadings of the new *WD-R* axis were 0.717 x *R* and -0.717 x *WD*. The final plot of all sites against the maximised *WD-R* axis is shown in Figure 6.7. Although some sites had large positive or negative loadings of the *WD-R* axis, the majority of sites were scattered across the range of values on the *WD-R* axis.

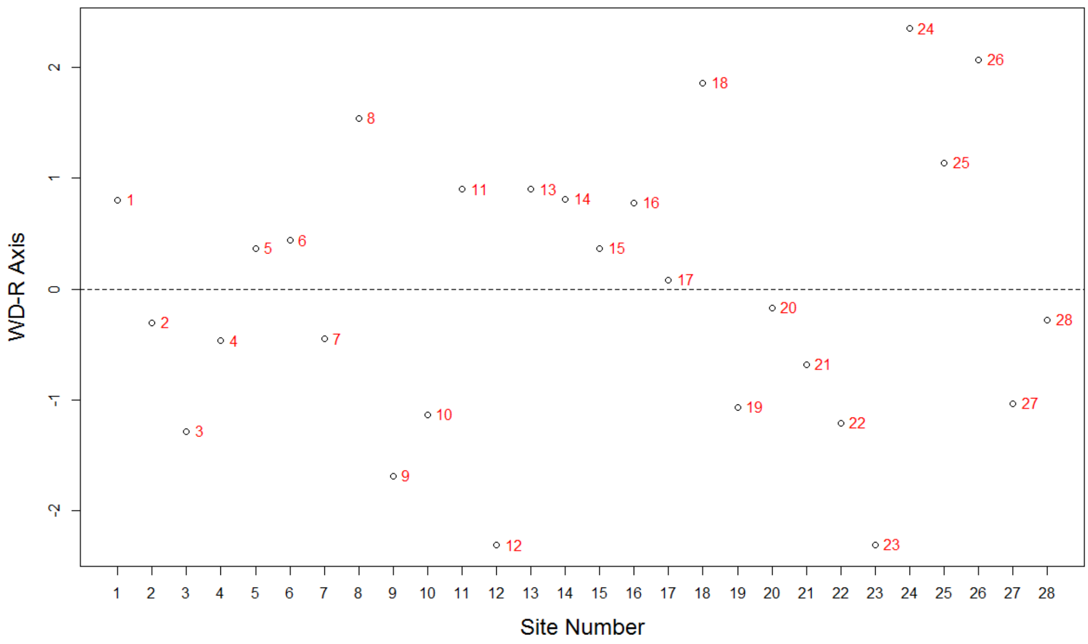


Figure 6.7. All 28 sites (TRAIN and TEST groups) plotted against the maximised *WD-R* axis.

Based on the separation of the sites based on the loadings of the enhanced *WD-R* axis (Figure 6.7), sites were divided into two groups. Thos with a *WD-R* axis loading > 1 were assigned to group 1 and sites with a loading < -1 were assigned to group 2 with sites falling between these values unassigned to a group (Table 6.11).

Table 6.11. Grouping of TRAIN and TEST sites based on WD-R axis of channel parameters.

	Group		
	1	**2**	**Ungrouped**
Site Number	8, 18, 24, 25, 26	3, 9, 10, 12, 19, 22, 23, 27	1,5, 6, 2, 4, 7, 11, 13, 14, 15, 16, 17 20, 21, 28

6.3.2. Discussion of channel parameter analysis

The underlying variability found in the channel parameter dataset was centred on the parameters *WD* and *R*. *WD* had the strongest influence on cross-sectional parameter variance across both PC1 and PC2 of PCA1, while *R* was the third strongest influence (Table 6.6). The direction of each channel parameter in relation to the orthogonal axes PC1 and PC2 of PCA 1 was examined in Figure 6.2. The parameters *D* and *R* operated in a similar direction, the parameters *W* and *P* also operated in a similar direction but orthogonal to other parameters, and *WD* was a single parameter acting in an orthogonal direction to other parameters.

The second PCA (PCA2), which was based on a reduced number of variables (*P*, *R* and *WD*), identified that the largest underlying variance in the dataset occurred when the data was projected along an orthogonal axis which had high values of *R* at one end and high values of *WD* at the other (Table 6.8). The second axis contained strong positive values of *P* and *WD* operating in the same direction. Hierarchical clustering of the projected values of PC1 and PC2 from PCA2 on the 164 cross-sections identified three groups (Table 6.9), which were also identified in the plot of the PC1 and PC2 loadings applied to the mean site values of channel parameters (Figure 6.4).

To test the wider applicability of grouping sites based on the orthogonal variability in channel parameters identified in the TRAIN group (Table 6.8), the loadings from PC1 and PC2 of PCA2 were then applied to the cross-sectional parameter values from the TEST group, as well as the mean site values of the TEST group. While plots and hierarchical clustering (Tables 6.10 and 6.11 and Figures 6.5 and 6.6) failed to identify strong natural groupings among the TEST sites, a small number of sites were separated into two groups through the loadings of PC1 of PCA2 (Table 6.11).

6.3.3. Analysis of remote parameters

The remote parameters of catchment area (A_d), slope (S), elevation (E), drainage density (D_d) and stream-power (Ω) from each of the 28 study sites are summarised in Table 6.12. Catchment area (A_d) ranged from 4.4 to 1360 km^2, with a mean of 301.3

km^2, slope (S) ranged from 0.0001 to 0.02 m/m with a mean value of 0.004, elevation (E) ranged from 6 to 413 m ASL with a mean value of 168.6 m ASL, D_d ranged from a minimum of 1.52 to 4.19 km/km^2 with a mean of 2.16 km/km and stream-power (Ω) ranged from 57.2 to 10 316.5 Wm^{-1} with a mean value of 2129.3 Wm^{-1}. *CV* for remote parameters ranged from 0.30 for *Dd* to 1.2 for Ω (Table 6.12).

Table 6.12. Summary of the remote parameters catchment area (A_d), slope (S), elevation (E), drainage density (D_d) and stream-power (Ω) from the 28 sites comprising the combined TRAIN and TEST groups.

	Mean	**Maximum**	**Minimum**	***CV***
A_d (km^2)	301.3	1360.5	4.4	1.18
S (m/m)	0.004	0.0200	0.0001	1.13
E (m ASL)	168 6	413.0	6.0	0.69
Dd (km/km^2)	2.16	4.19	1.52	0.30
Ω (Wm^{-1})	2129.3	10316.5	57.2	1.2

To examine the distribution of remote parameter values amongst the 28 sites and the relationships between remote parameters a scatterplot matrix was produced (Figure 6.8). The distribution of a number of the remote parameters were significantly skewed, particularly A_d, D_d and Ω (Figure 6.8), but no strong correlations between remote parameters was visible in the scatter plots. The only significant correlation found between the remote parameters from the TRAIN group of sites at p <0.005 level of significance was between S and Ω (0.727) (Table 6.13), although *Ad* and *S* showed a negative correlation (-0.671) at p < 0.05 level of significance.

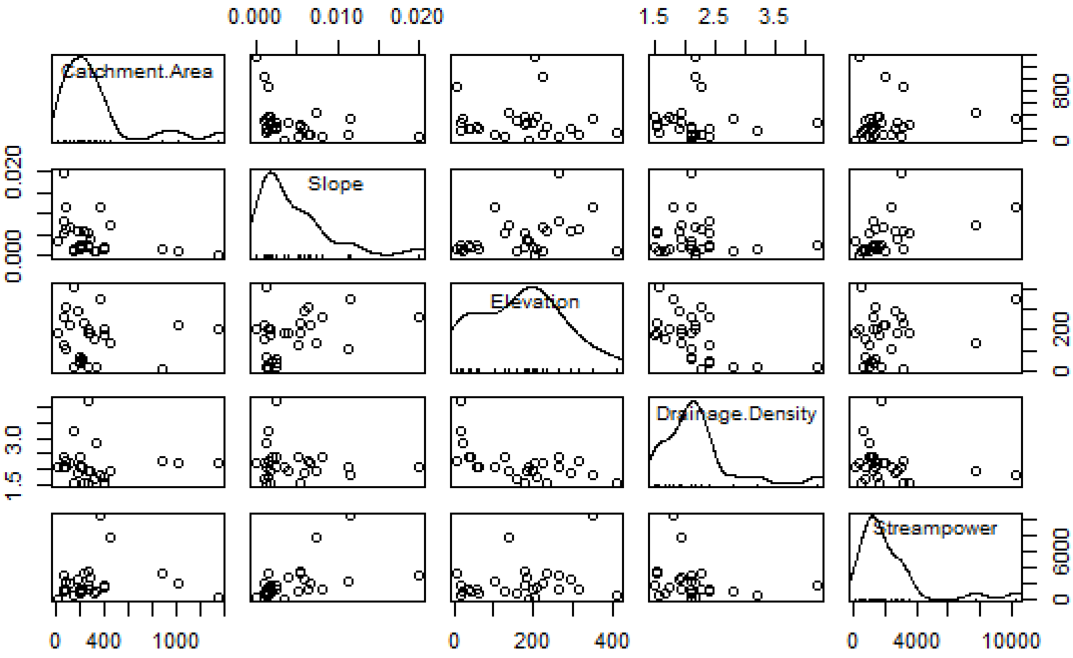


Figure 6.8. Scatterplots and histograms (centre diagonal plots) of remote parameters from 28 TRAIN and TEST sites for catchment area (A_d), slope (S), elevation (E), drainage density (D_d) and stream-power (Ω).

Table 6.13. Linear (Pearson) correlation coefficients for remote parameters from the 13 TRAIN sites. All correlations have p values < 0.005 unless otherwise noted in brackets. (A_d = catchment area, S = slope, E = elevation, D_d = drainage density and Ω = specific stream-power).

Parameter	***S***	***E***	***Dd***	**Ω**
Ad	-0.671 (0.012	-0.182 (0.552)	0.084 (0.786)	-0.346 (> 0.1)
S		0.393 (> 0.1)	-0.108 (> 0.1)	0.727 (< 0.005)
E			-0.387	0.151
D_d				-0.401

A PCA using the remote parameters catchment area (A_d), slope (S), elevation (E), drainage density (D_d) and stream-power (Ω) was undertaken on the 28 sites that comprise the combined TRAIN and TEST groups (PCA3). The standard deviation and variance of each component of PCA3 is shown in Table 6.14, the composition of the first three components of PCA3 is shown in Table 6.13, and a plot of sites against the results of PCA3 is shown in Figure 6.9. The proportion of variance of the first principal component (0.411) was relatively low. Combined with PC2 (0.241) and PC3 (0.195), the variance explained by the first three components of PCA3 was just over 85% (Table 6.14).

Table 6.14. Standard deviation and variance of first three principle components (PC1, PC2 and PC3) of the principle components analysis (PCA3) on 28 sites comprising TRAIN and TEST group using the catchment area (A_d), slope (S), elevation (E), drainage density (D_d) and stream-power (Ω).

	PC1	**PC2**	**PC3**	**PC4**	**PC5**
Standard Deviation	1.434	1.115	0.987	0.671	0.524
Proportion of Variance	0.411	0.241	0.195	0.090	0.055
Cumulative Variance	0.411	0.660	0.855	0.945	1.000

Table 6.15. Composition of the first three principal components (PC1, PC2 and PC3) of PCA3 based on remote parameters (A_d = catchment area, S = slope, E = elevation, D_d = drainage density and Ω = stream-power).

	A_d	S	E	Dd	Ω
PC1	0.179	-0.526	-0.538	0.436	-0.460
PC2	-0.711	0.443	-0.246	0.487	-0.033
PC3	0.476	0.218	-0.343	0.370	0.687

The first component (PC1) of PCA3 consisted of strong negative influence of S, E and Ω and a positive D_d value, PC2 was composed of very strong negative influence of A_d and positive S and D_d, while PC3 was composed of strong positive Ω and A_d, and weaker values of other parameters (Table 6.15).

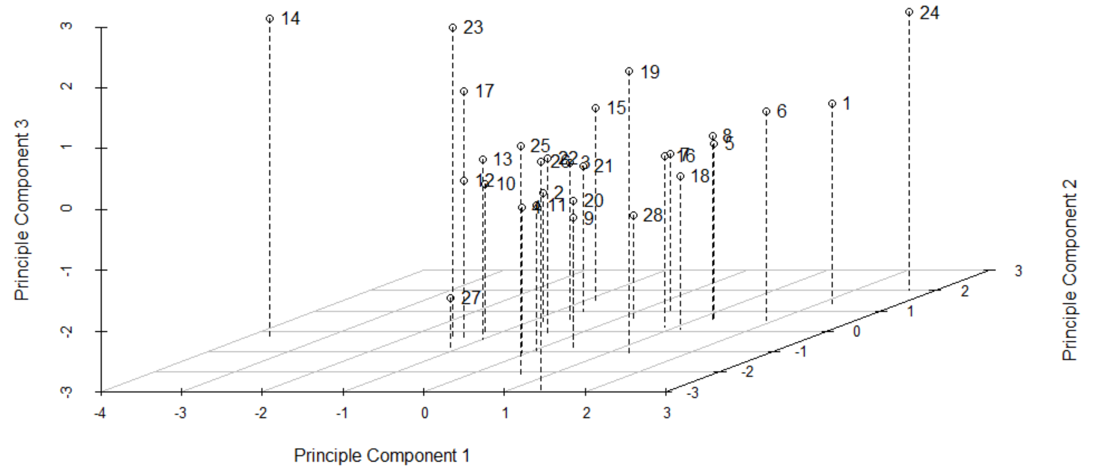


Figure 6.9. All sites (both TRAIN and TEST group) plotted against the first three principal components (PC1, PC2 and PC3) of PCA3 which was based on the remote parameters catchment area (A_d), slope (S), elevation (E), drainage density (D_d) and stream-power (Ω).

Due to the low amount of variance explained by the first two components of PCA3 (Table 6.14), the first three components of PCA3 were included in the analysis of underlying variation in the remote parameter site data. A plot of the 28 sites against the first three principal components of PCA3 is shown in Figure 6.9. Sites 1 and 24 were separated from other sites by positive values of PC1 while site 14 was separated from other sites by strong negative values of PC1. Site 24 was also at the upper end of positive PC2 values, while site 22 had strong negative PC2 values. Sites 14, 23 and 24 had strong positive PC3 values, and site 27 was separated from other sites by strong negative PC3 values (Figure 6.9).

To identify natural groupings of sites based on the results of PCA3, a hierarchial clustering of the 28 sites comprising TRAIN and TEST groups was conducted using loadings from PC1, PC2 and PC3 of PCA3 (which was based on the remote parameters A_d, S, E, D_d and Ω), and the results are shown in Table 6.16. Due to the large variations in loadings from PC1, PC2 and PC3, the majority of sites were clustered into one group. Sites 14 and 23 assigned to group 2, site 17 assigned to group 3, sites 19, 25 and 26 assigned to group 4 and site 24 assigned to group 5, and all other sites were assigned to group 1.

Table 6.16. Hierarchial clustering of the 28 sites comprising TRAIN and TEST groups using loadings from the first three principal components (PC1, PC2 and PC3) of PCA3 which was based on the remote parameters catchment area (A_d), slope (S), elevation (E), drainage density (D_d) and stream-power (Ω).

Group	**1**	**2**	**3**	**4**	**5**
Site	1,2,3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16, 18, 20, 21, 22	14, 23	17	19, 25, 26	24

6.3.4. Discussion of remote parameter analysis

The analysis of remote parameters (PCA3) indicated that the underlying variation in the dataset of all sites was spread over a number of components, with no single orthogonal combination of variables explaining a high proportion of the variance (Table 6.14). The composition of each component consisted of portions of most parameters, with no single parameter dominating (Table 6.15). Hierarchical agglomerative clustering of sites based on the first three principal components of PCA3 resulted in the majority of sites being assigned to a single group, with outliers in the data being the sole members of a number of groups (Table 6.16). The only correlations between the groupings derived from channel parameters and the groupings derived from remote parameters were sites 25 and 26 which were assigned to small separate groups in both analyses (Tables 6.11 and 6.16). Based on these results, it was determined that combinations of the remote parameter values determined using PCA were unable to reproduce natural grouping identified using channel parameters.

6.3.5. Deriving channel based grouping of sites using remote parameters

The strongest source of underlying variance identified amongst the channel cross-sectional parameter values was an ordinal axis that was orientated between negative values of *WD* and positive values of *R*. To assess the ability of the remote parameters to predict a gradient of *WD* and *R* values that reflect those from the channel parameter analysis, regression of the remote parameters against *WD* and *R* values was undertaken. Following common practice, A_d was log transformed prior to analysis to reduce skew. Although the distribution of values of *E* and Ω were also skewed (Figure 6.13), these parameters were left untransformed as they both possess significant tails which, after investigation, were found to be relevant to the analyses and lost if transformed. To enhance predictive ability, stream order (SO) values for each site, derived from the CFEV database, were also included. A sequential multiple regression analysis with backward elimination was used to develop a model to predict *WD* from remote parameters, and basic descriptive statistics and regression coefficients of the analysis are shown in Table 6.17. All remote parameters (D_d, log A_d, Ω, *S*, SO and *E*) were used in the initial regression analysis, with the least significant predictor variable removed at each step. Elevation, SO, *S*, and *SP* were sequentially removed, and each step saw a progressive decrease in R^2 values and increase in adjusted R^2 values. The final model found that both predictors D_d and log A_d had significant correlations (< 0.005) with R, and in conjunction explained just under 52% of the variance in R (Table 6.17).

Table 6.17. Summary of regression variables for prediction of hydraulic radius (R). *N* = 28 (standard deviations from the mean).

	Model 1		**Model 2**		**Model 3**		**Model 4**		**Model 5**	
	β	*ρ*	β	*ρ*	β	*ρ*	β	*ρ*	β	*ρ*
D_d	0.343 (0.194)	0.091	0.363 (0.130)	0.011	0.377 (0.123)	0.006	0.376 (0.122)	0.643	0.389 (0.117)	0.003
log A_d	0.227 (0.159)	0.167	0.240 (0.126)	0.070	0.279 (0.079)	0.002	0.248 (0.061)	0.005	0.241 (0.058)	0.000
Ω	0.00 (0.00)	0.442	0.00 (0.00)	0.436	0.00 (0.00)	0.448	0.00 (0.00)	0.029		
S	16.76 (25.53)	0.519	15.490 (23.35)	0.514	14.52 (22.80)	0.530				
SO	0.084 (0.215)	0.701	0.064 (0.162)	0.695						
E	0.00 (0.001)	0.889								
R^2	0.535		0.534		0.531		0.523		0.518	
Adjusted R^2	0.402		0.429		0.449		0.463		0.480	

A sequential multiple regression analysis was also used to predict *WD* from remote parameters, and basic descriptive statistics and regression coefficients of the analysis are shown in Table 6.18. All remote parameters were used in the first step, and the least significant predictor variable was removed at each stage. R^2 remained constant throughout the 3 step model, but adjusted R^2 steadily increased. The final model found that D_d was the only predictor variable with a significant (negative) correlation (< 0.1) and explained just over 27% of the variance in *WD*.

Table 6.18. Summary of linear regression variables for remote parameter prediction of width-to-depth ratio (*WD*). N = 28 (standard deviations from the mean).

	Model 1		Model 2		Model 3	
	β	ρ	β	ρ	β	ρ
D_d	-6.051 (4.951)	0.235	-6.446 (3.325)	0.065	-6.531 (3.181)	0.052
Ω	0.001 (0.001)	0.379	0.001 (0.001)	0.370	0.001 (0.001)	0.323
S	-113.80 (652.1)	0.863	-88.582 (596.3)	0.883	-111.6 (553.8)	0.842
SO	1.105 (5.489)	0.842	1.489 (4.134)	0.722	1.879 (2.571)	0.472
log A_d	0.653 (4.051)	0.873	0.394 (3.217)	0.904		
E	0.003 (0.027)	0.914				
R^2	0.274		0.274		0.273	
Adjusted R^2	0.067		0.109		0.147	

To investigate whether stream-power was a better predictor of *R* and *WD* along a single river, a linear regression analysis was performed on a subset of the full data set consisting of the six sites located along the Ringarooma River and its major tributary the Dorset River (sites 3, 19, 20, 21, 22 and 23; Table 6.19). Due to the small number of degrees of freedom associated with the small sample size, not all predictor variables could be included in the analysis. D_d was chosen in conjunction with Ω due to the association between D_d and *R* and between D_d and *WD* found previously (Table 6.17and Table 6.18). Multiple linear regression analysis was used to develop a model for predicting *R* and *WD* from the remote parameters Ω and D_d for the subset of sites, and basic descriptive statistics and regression coefficients of the analyses are shown in Table 6.19. Neither predictor variable had a significant ($p < 0.01$) correlation with

R, and there were also no significant correlations between the predictors R and Ω and the variable WD, despite Ω having a significant p value (< 0.1).

Table 6.19. Summary of regression variables for both hydraulic radius (R) and width-to-depth ratio (WD) against predictor variables Drainage density (D_d) and stream-power (Ω) for sites in the Ringarooma Catchment. N = 6 (standard deviations from the mean).

	R		***WD***	
	β	ρ		
Ω	0.00 (0.00)	0.384	0.003 (0.001)	0.052
D_d	-0.341 (0.423)	0.479	-0.010 (11.418)	0.999
R^2	0.287		0.799	
Adjusted R^2	-0.189		0.665	

6.3.6. Discussion of attempts to derive channel parameter groupings

Multiple linear regression of the remote parameters to derive a gradient of WD and R values that could be used to group sites had mixed results. The remote parameters Dd and A_d showed a reasonable ability to predict R values (Table 6.17), however attempts to predict WD values were less successful (Table 6.18).

Stream-power was proposed as a strong predictor candidate but showed little correlation with R or WD. As downstream changes in stream-power are likely to vary considerably even between streams within a single watershed because of different patterns of flow addition but largely because of variations in slope at the profile and local scales (Knighton, 1999a), it was hypothesised that comparisons of stream-power values along a stream are more likely to demonstrate differences between channel morphology types. However the predictive capacity of Ω was not improved on a subset of sites along a single river.

6.3.7. Discussion of overall results

This study used the river and catchment metrics developed in earlier chapters in conjunction with field collected parameters and remotely sensed data in an attempt to develop a simple objective and quantitative grouping of river reach sites. The analysis of variability in the channel parameters identified that the largest underlying variance in the dataset occurred when the data was projected along an orthogonal axis which had high values of *R* at one end and high values of *WD* at the other. The *WD-R* axis offers an intuitively important and meaningful delineation between sites that links both hydrology and geomorphology, and is potentially ecologically meaningful. It's possible use in typology is also supported by the findings of a number of other studies. Knighton (1981) found riffle sections in New Zealand streams were distinguished from pool sections in having wider and shallower channels, when considering small localised stream lengths. De Rose et al. (2008) found the width-to-depth ratio characteristically decreased with increasing distance along the lower reaches of most rivers. They also found a gradient of river basins existed, from those where width variations between sites drive variations in cross section area and hence discharge, to those where depth variations are more important. Those basins where width was the dominant variant in cross-sectional area tending to be inland, and those where variations in depth dominated cross-sectional variability tending to occur on the coast De Rose et al., 2008). Small headwater streams have been found to be distinguished by a high ratio of structural component size (rock, tree roots, woody debris etc.) in relation to stream width, due to the stream's lack of competence to move the material that forms its bed and banks (Gooderham et al., 2007). This complexity in channel cross section would result in increased wetted perimeter in relation to the cross-sectional area and may allow these headwater streams to be distinguished from less complex river reaches downstream. On the hypothesis that catchment scale parameters control the range of channel morphology forms that occur at smaller scales, attempts were made to reproduce the groupings of sites that were based on channel morphology parameters using remotely acquired parameters. However the methods used were unable to reproduce natural grouping identified using channel parameters.

The strongest grouping of sites identified using remote parameters contained three sites: The South Esk River at Malahide (26), The south Esk River at Ormley (26) and the Ringarooma River at wetlands (19). These sites were distinguished from other sites by large catchment areas, but had disparate *WD* and *R* values and no obviopus similarities in channel morphology. The Ringarooma River at wetlands was a broad, shallow sand bed river with high WD values and low R values, while the other two sites had relatively deep channels with high R values and relatively low WD values. These sites did show a strong similarity in having the three largest channel widths, but this was a result of the well recognised correlation between channel width and catchment area.

As stream-power has been found to have a strong influence of channel morphology (Knighton, 1999a), and has previously been used in hydromorphological typologies (Schmitt et al., 2007, Orr et al., 2008), it was identified as a strong potential candidate for a predictor variable. However stream-power was found to have little effect on the underlying variability in the dataset and was a poor predictor of *WD* or *R* values, either for the north-east region overall or for a small subset of sites located on the same river. Schmitt et al. (2007) used agglomerative hierarchical clustering, principal component analysis and multiple correspondence analysis to develop a quantitative hydromorphological typology of river types, with stream-power as a major classification criteria. However it did not lead to a functional typology due to important overlap in stream-power values between groups (Stott, 2010). Jain et al. (2008) also found no well defined total stream-power range to distinguish between rivers in different valley settings. This study did identify drainage density as a factor that could be used in developing a typology of rivers, as it was the strongest predictor of *WD* and R values. Literature reviews did not reveal any previous use of drainage density as a parameter in hydromorphological typologies.

There are many potential sources of error and uncertainty in this study. Estimates of the values of channel parameter may be biased by the position of the cross-section in the catchment, or the type of channel (Bartley and Rutherfurd, 2005). A large sampling variability exists as a result of the relatively small sample size in this study, but that does not mean that the results of this study are meaningless. Regularities in time and space can still be observed as repeated patterns of landforms, and interpretations of these patterns can support efforts to meaningfully transfer understandings (Brierley et al., 2013). It is also possible that the river channel dimensions from the sites chosen in this study may not reflect current hydrological processes as channel form reflects influences of climate, tectonic activity, and human effects, over timescales from the Pleistocene to the present (Kondolf et al., 2003). Inherited geomorphological features, for example, can have a considerable influence on present channel dynamics (Schmitt, 2007), and rivers in different evolutionary phases may present different catchment controls- reach response relationships. Increasing the number of sites sampled and the number of cross-sections at each site would reduce the sampling error, while the use of multiple lines of evidence to establish bankfull stage would reduce the uncertainty associated with bankfull stage parameters. In addition, other methods of analysis may provide better understanding of underlying variation in the dataset. Also as relationships between parameters are often not linear, component analysis methods that are able to consider non-linear relations between variables may be more successful than PCA, which only considers linear correlations (Schmitt et al., 2007).

6.4. Conclusion

The aim of this study was to develop an objective and quantitative method to group north-eastern Tasmanian rivers and streams into hydromorphologically meaningful groups. To achieve this aim, several sub-studies were conducted in previous chapters to determine suitable methods and estimates of parameters for use in the development of a hydromorphological typology in this chapter. The sub-studies focussed on the estimation of the magnitude and frequency of small floods, investigation of bankfull channel morphometry, analysis of the first order estimates of peak discharge of small floods, and assessment of the hydromorphological characteristics of different rivers and catchments.

This chapter used the river and catchment metrics developed in earlier chapters in conjunction with multivariate statistical analysis of channel cross-sectional data from field surveys to investigate variability in channel morphology and develop a quantitative morphological typology. A strong source of underlying variability in the dataset was found to occur along an orthogonal axis which had high values of width-to-depth ratio at one end and high hydraulic radius values at the other. Methods to derive the groupings of sites based on channel parameters using remote parameters were generally unsuccessful. It was suggested that within reach variability confounded any attempts to identify between reach variability. However drainage density was identified as a strong remotely sensed predictor variable.

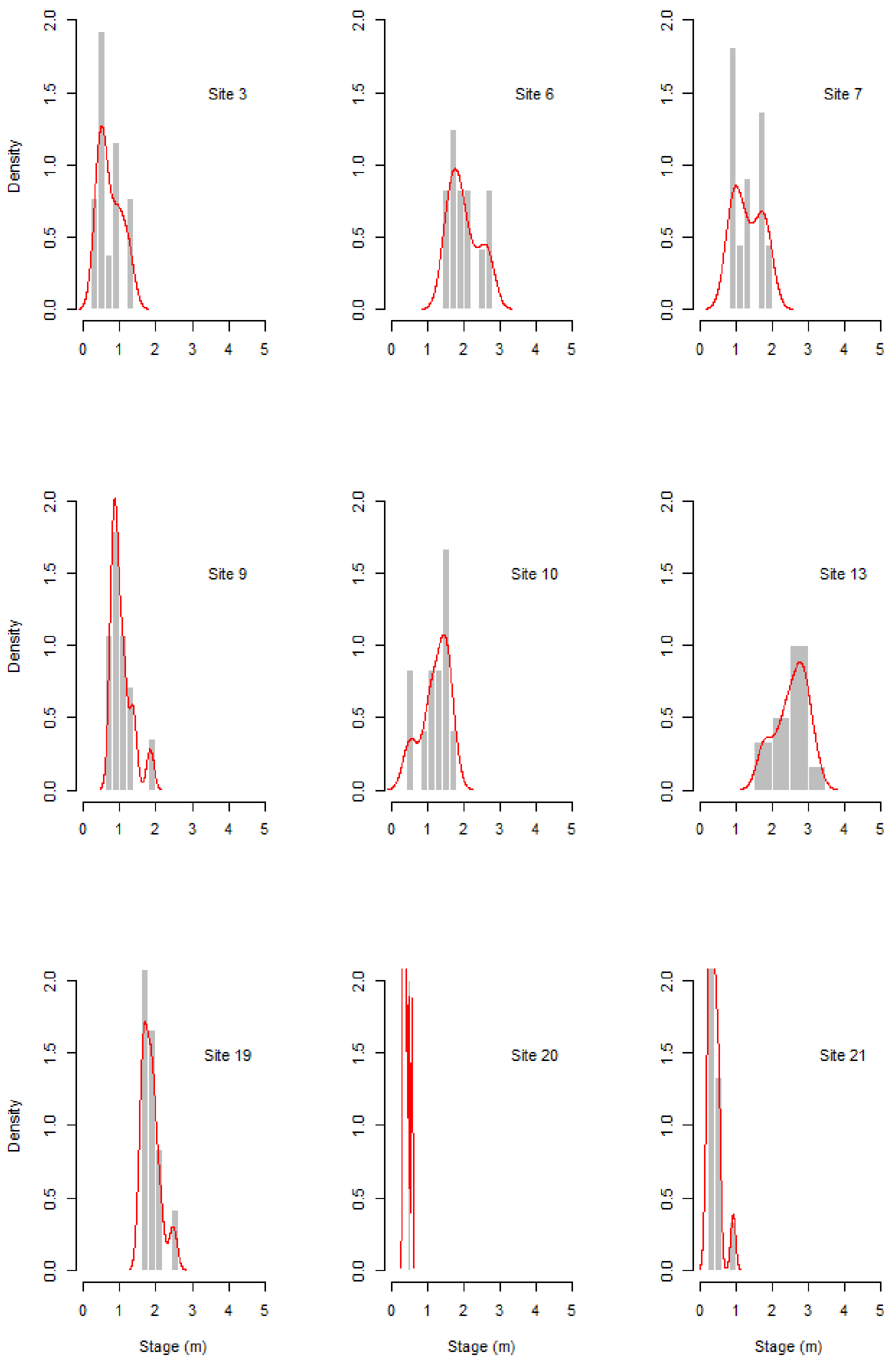
While there is no substitute for primary data collection, field work and a detailed expert-driven approach where possible (Dollar et al., 2006), an objective quantitative desktop methodology to provide meaningful hydrological, geomorphological and ecological groupings of sites offers great benefits to river management, and particularly the development of environmental flow regimes. Although a suitable typology was not developed in this study, the methods trialled offer potential for the further development of an objective and quantitative hydromorphological classification of north-eastern Tasmanian rivers based on spatial rather than intensive fieldwork techniques.

The methods used in this study offer insights into the development of an objective and quantitative morphological typology of north-eastern Tasmanian rivers. The results suggest that localised and reach scale factors have more influence on channel morphology than catchment controls in north-eastern Tasmanian rivers, and that nested catchment controls identified elsewhere may not be as relevant to north-eastern Tasmanian rivers. This has implications for the use of remotely sensed data and GIS tools in the study of regional hydromorphological characteristics

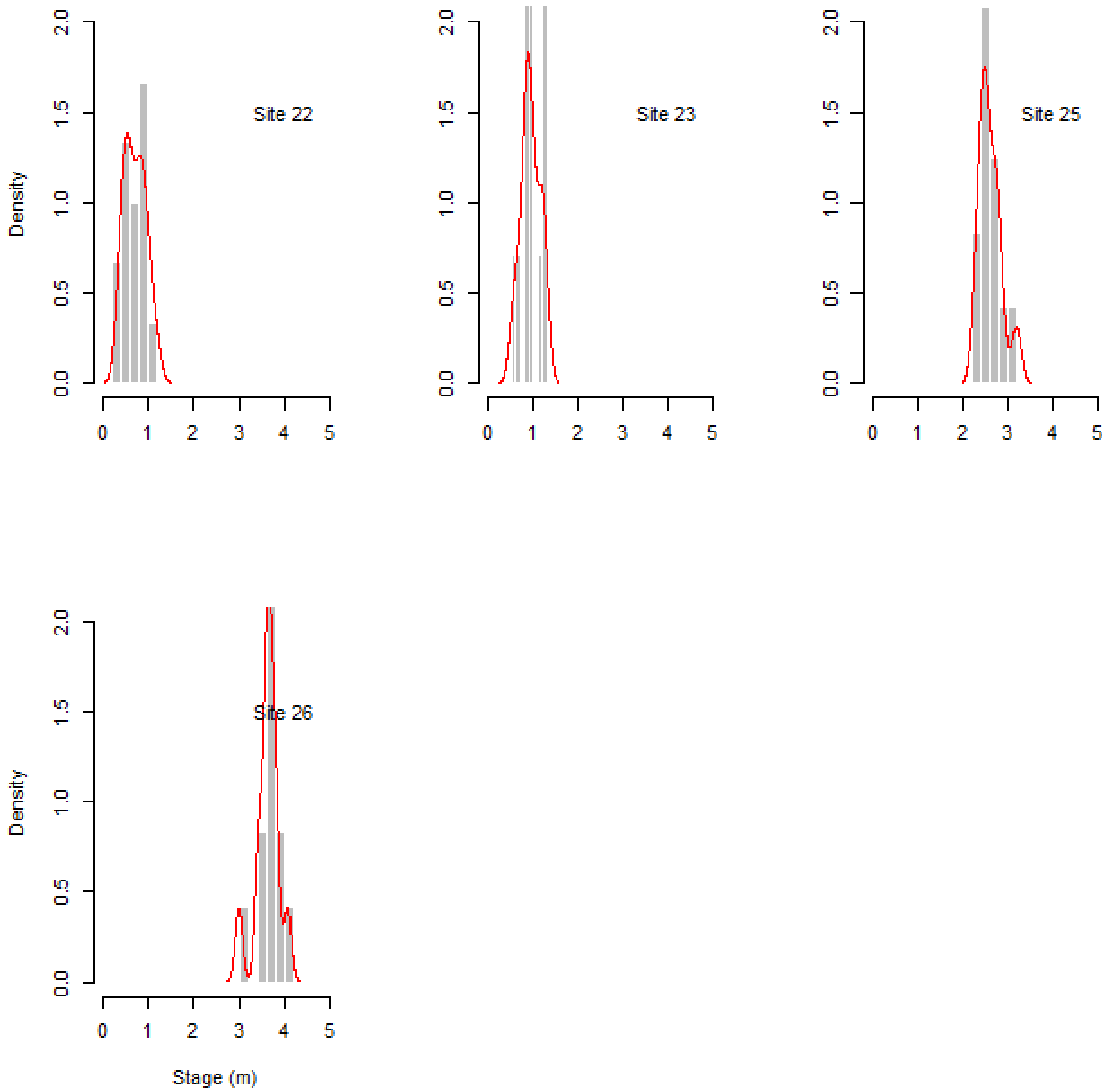
Appendix 6.1: Probability density plots of channel morphology parameters

Chanel morphology variability as expressed through probability density plots for a) depth (or stage); b) cross sectional area; c) wetted perimeter; d) width; e) hydraulic radius; and f) width-to depth ratio. Density estimates use a Gausian function for smoothing kernels with the bandwidth set at 0.9 times the minimum of the standard deviation.

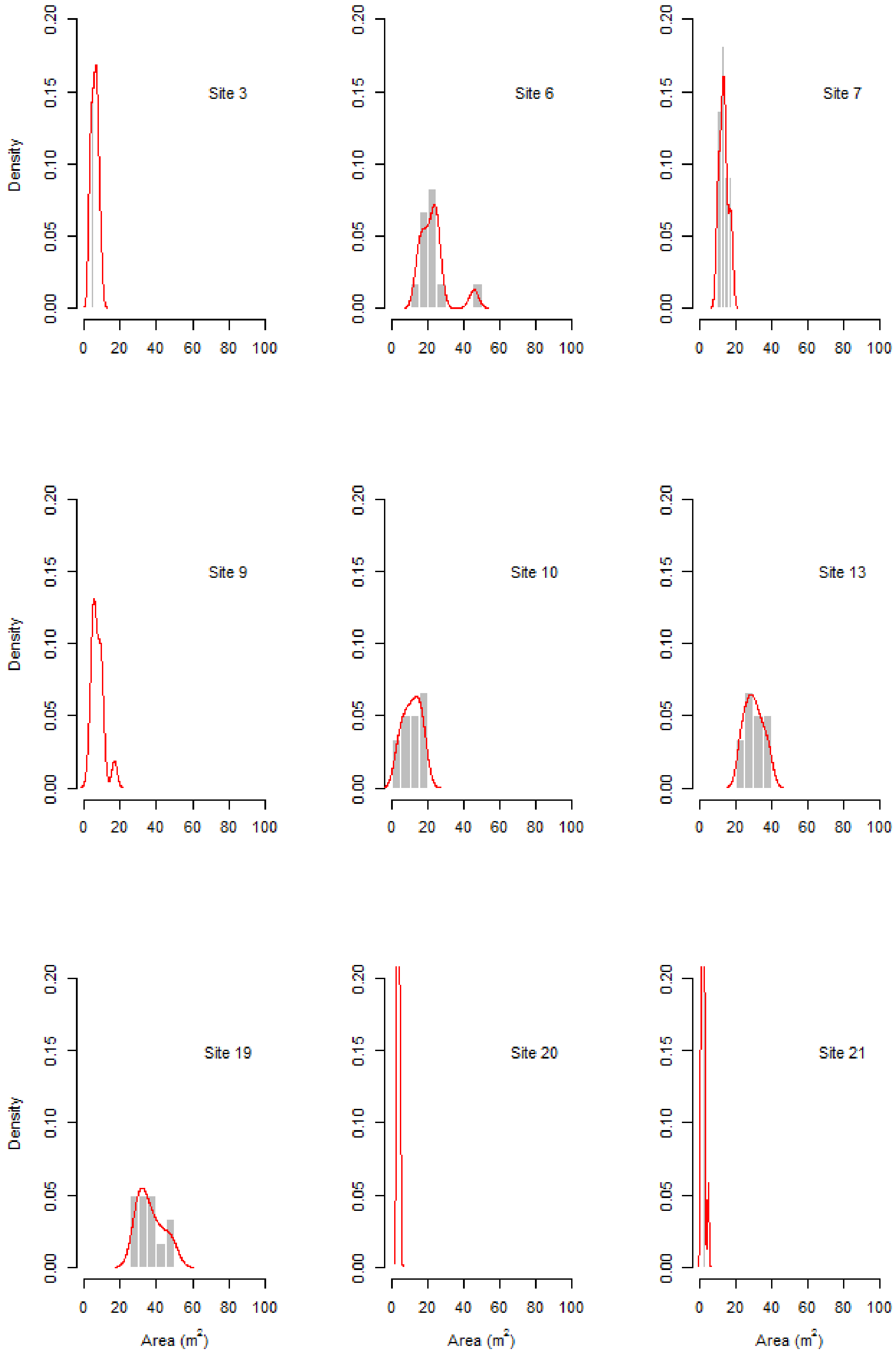
a. Depth



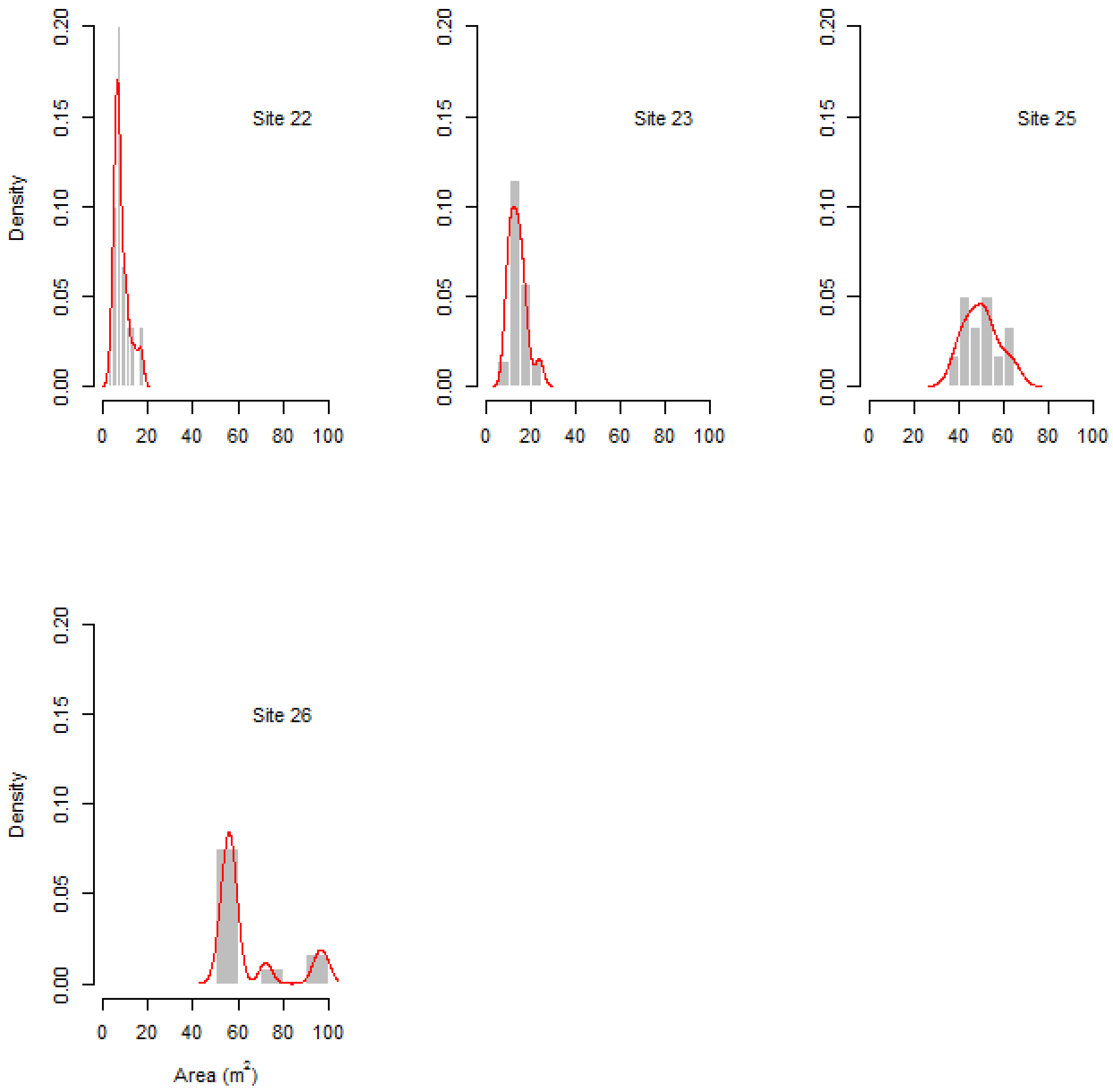
a. Depth (continued)



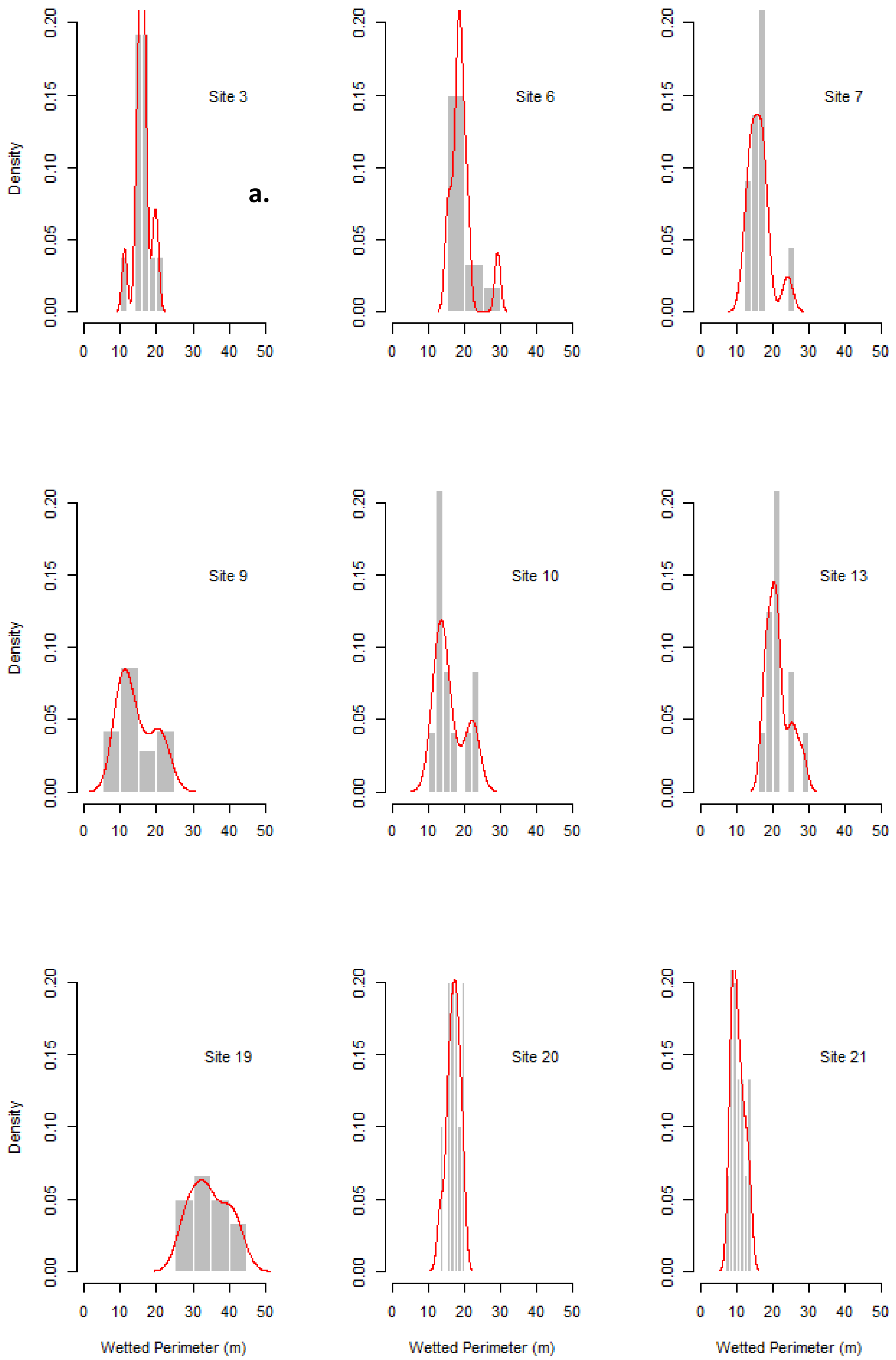
b. Cross sectional area



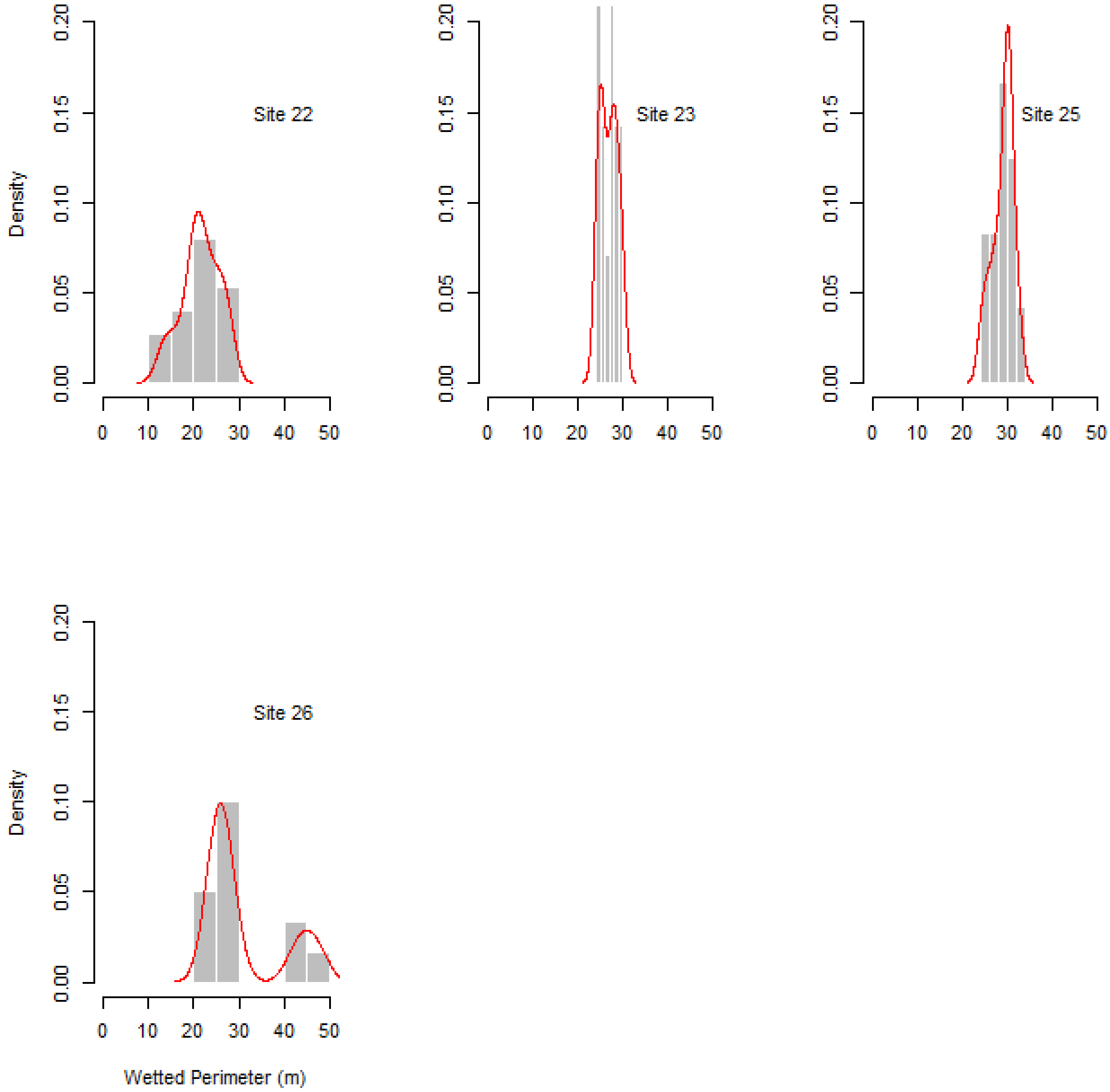
b. Cross sectional area (continued)



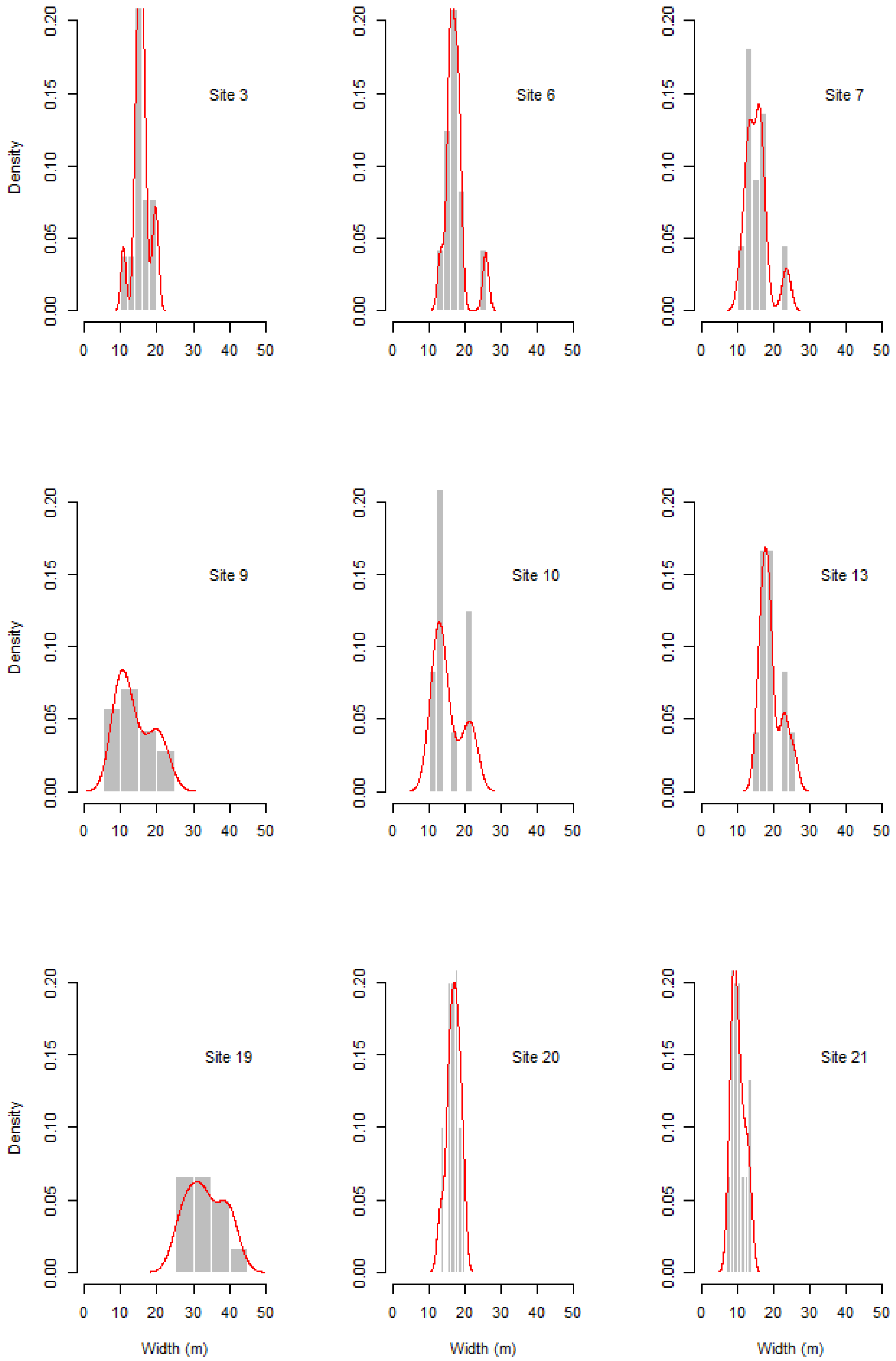
c. Wetted Perimeter



c. Wetted Perimeter (continued)

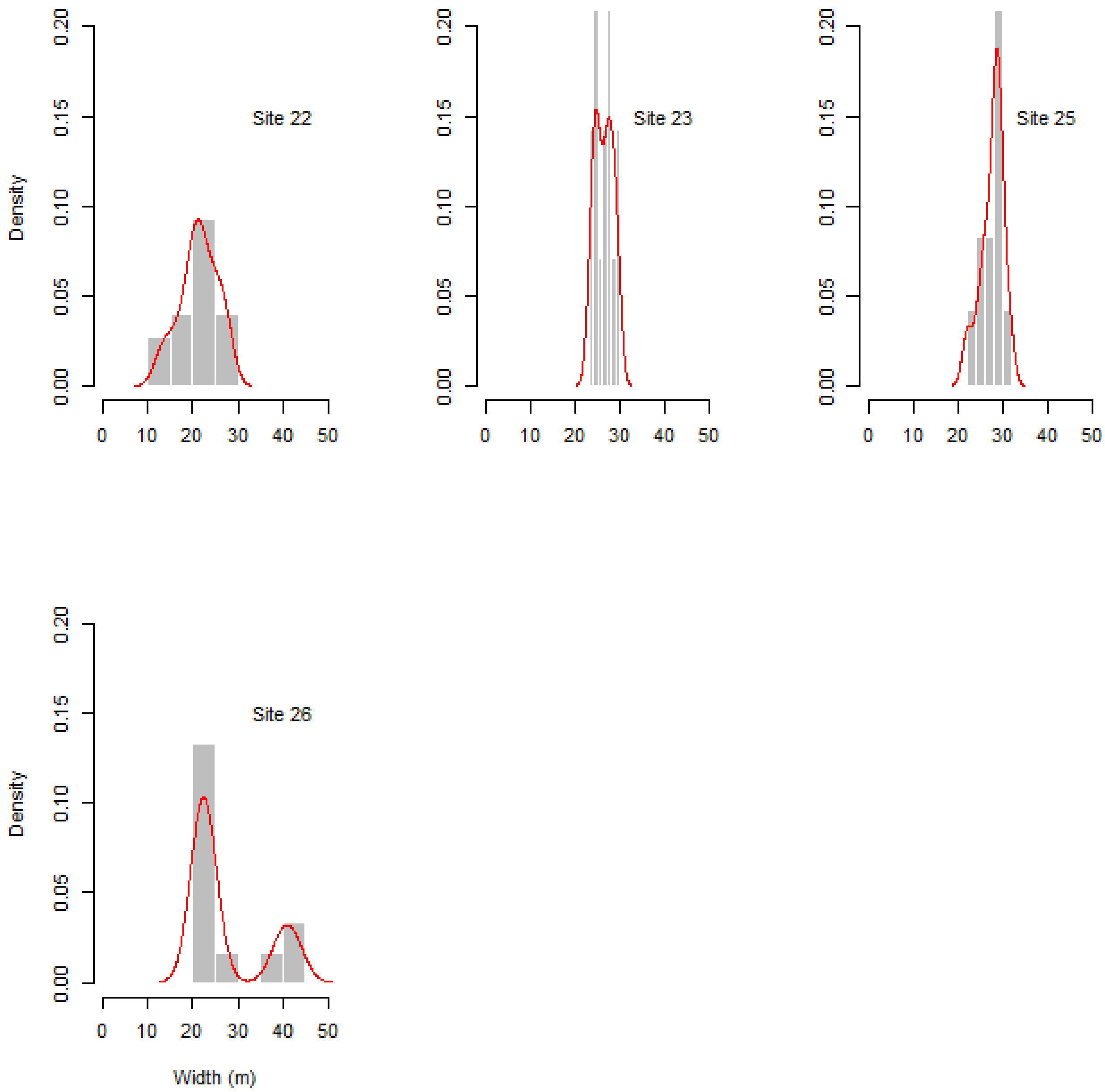


d. Width

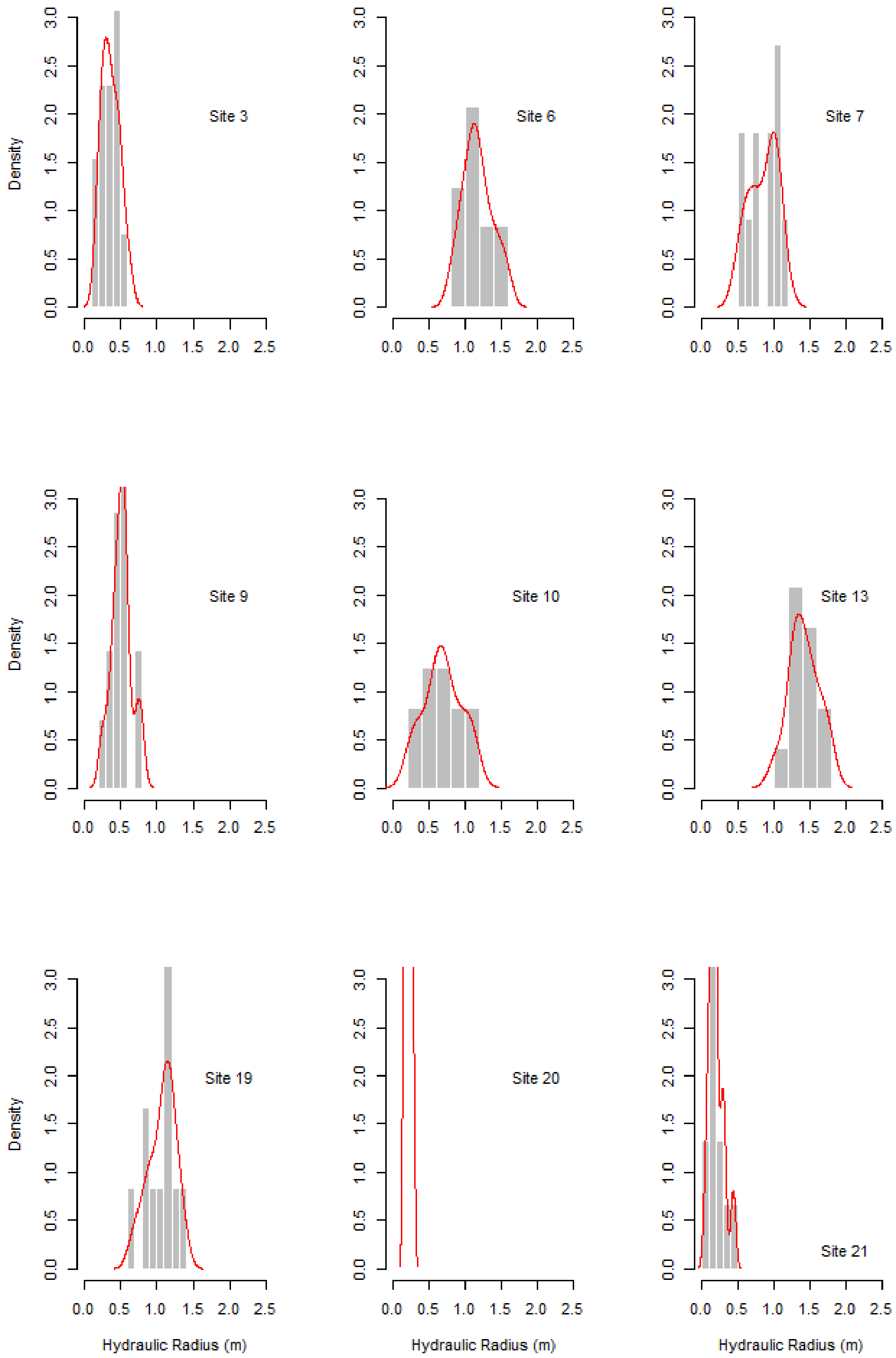


Site 3
Site 6
Site 7
Site 9
Site 10
Site 13
Site 19
Site 20
Site 21
Density
Width (m)

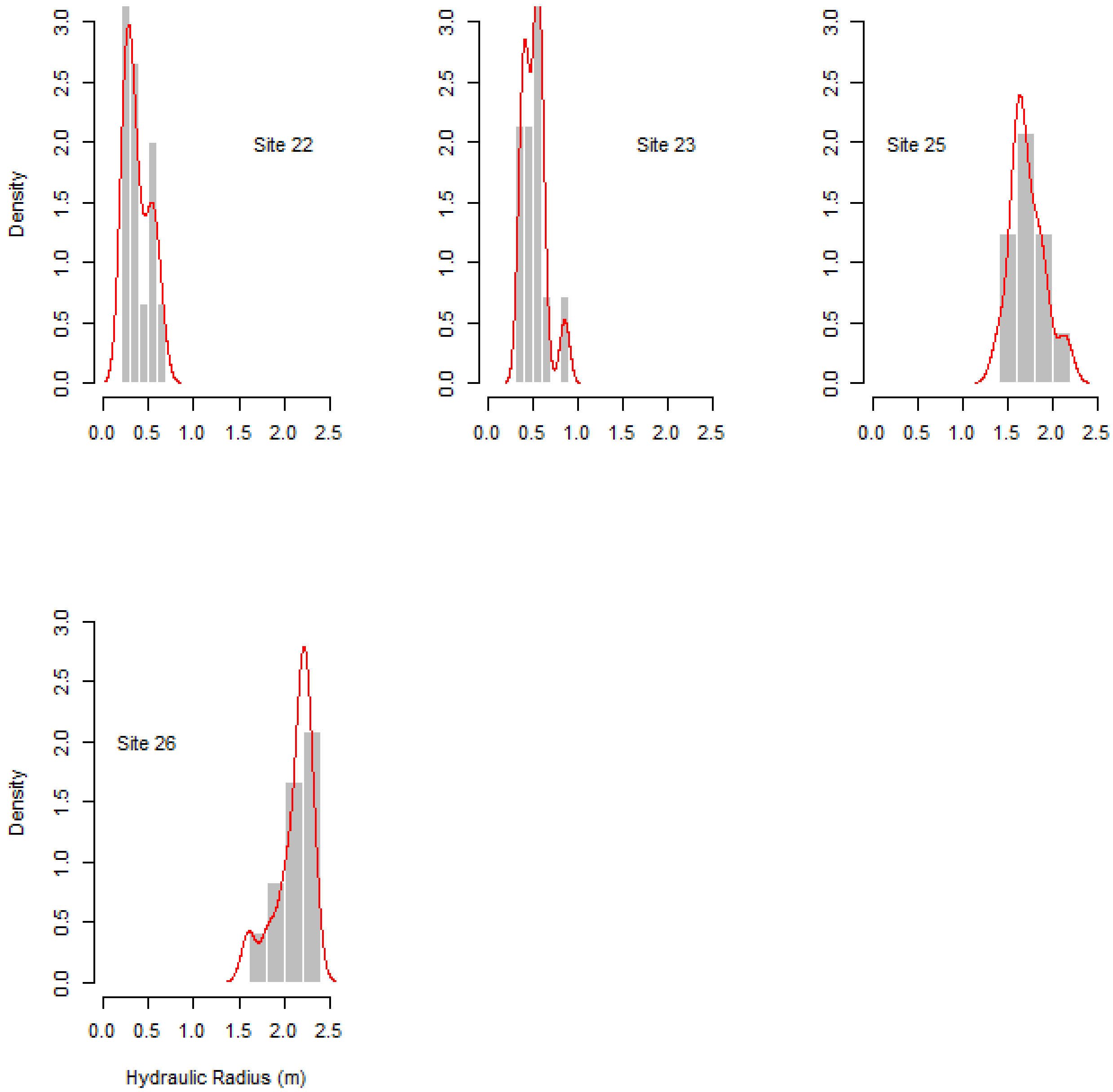
d. Width (continued)



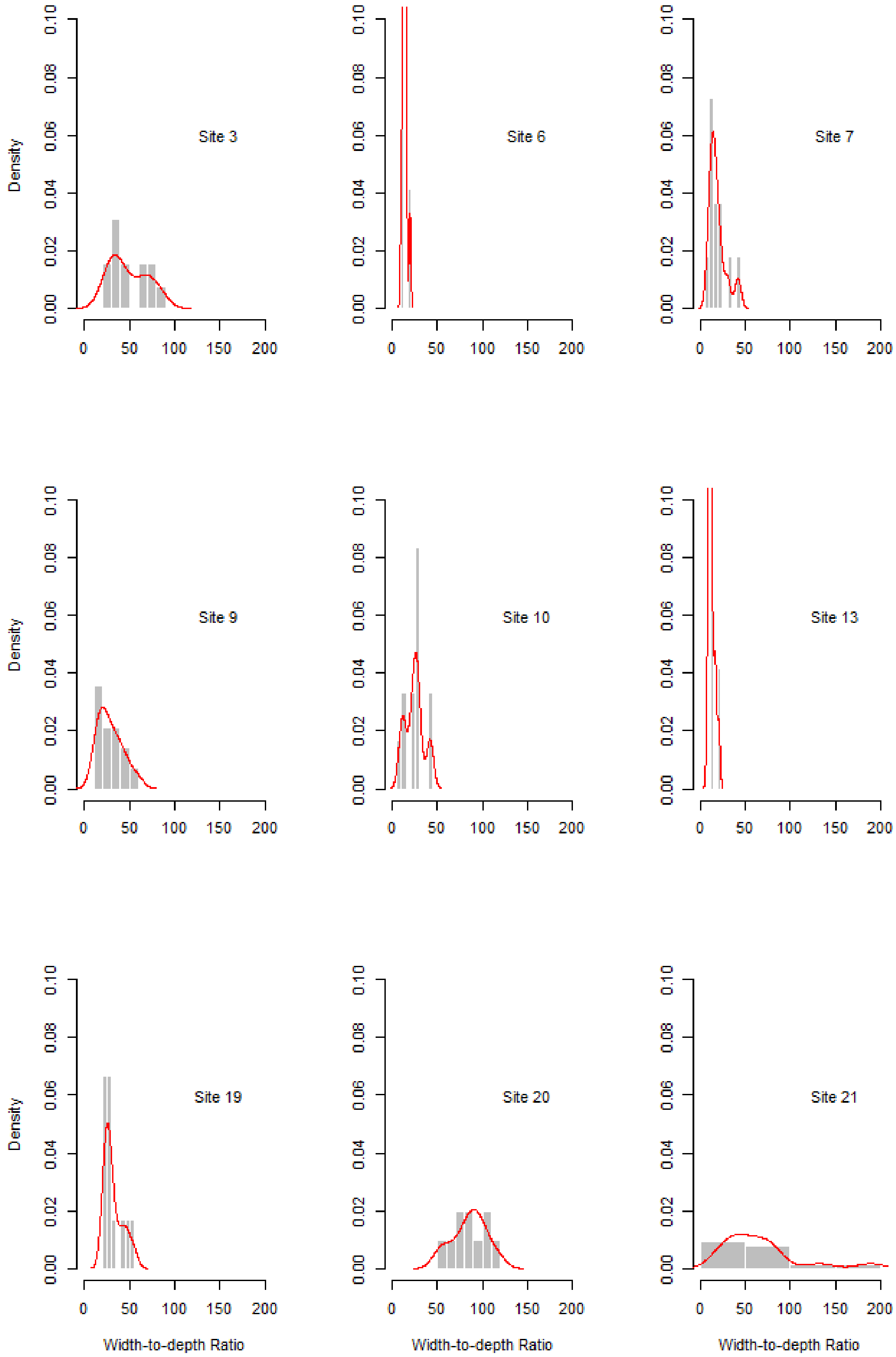
e. Hydraulic Radius



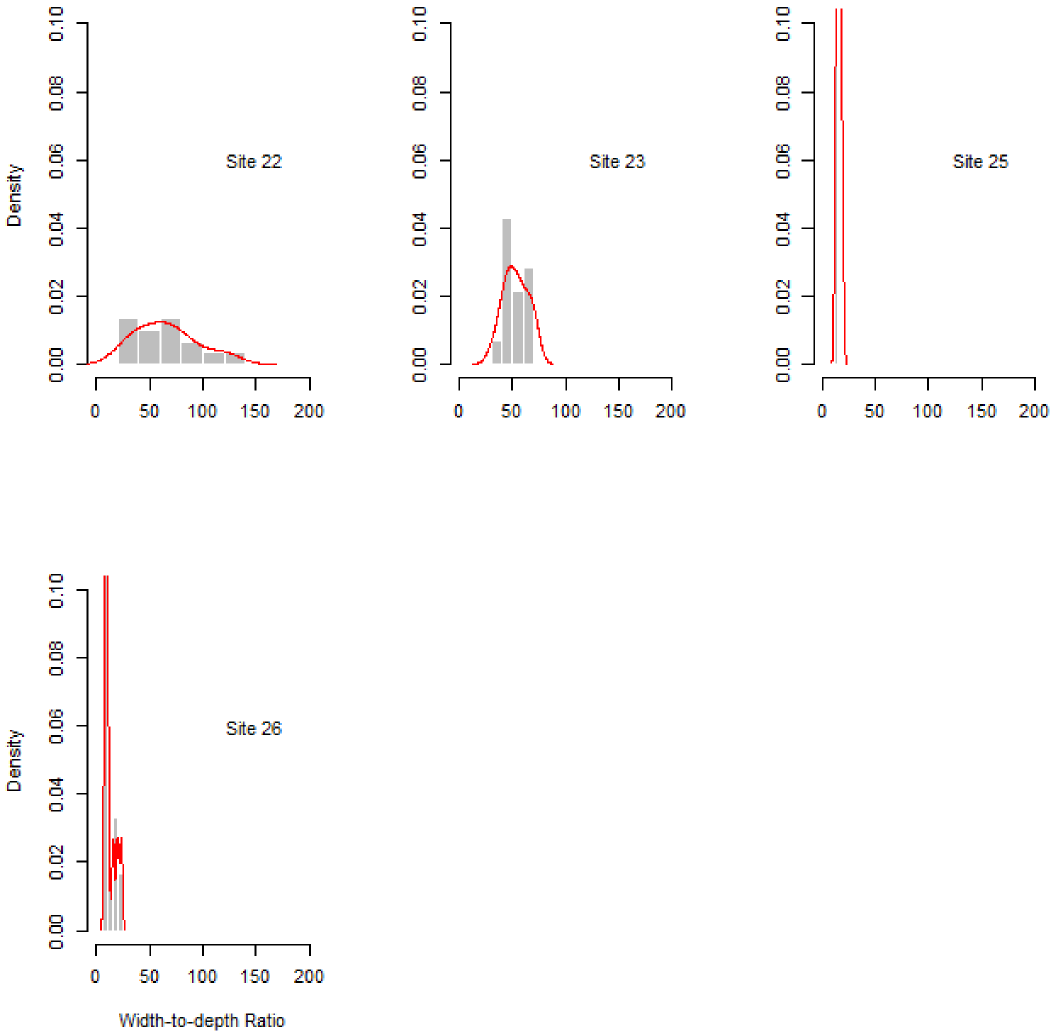
e. Hydraulic Radius (continued)



f. Width-to-depth ratio

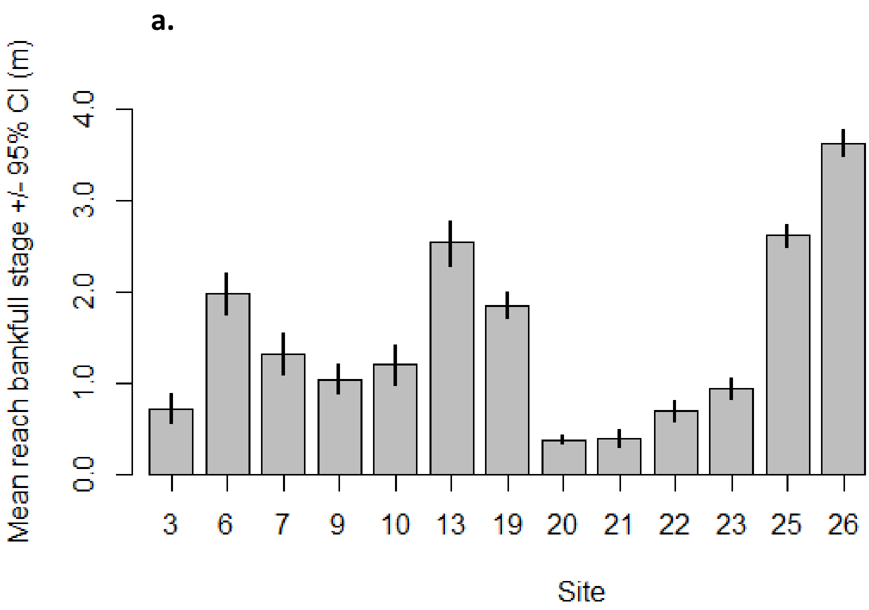


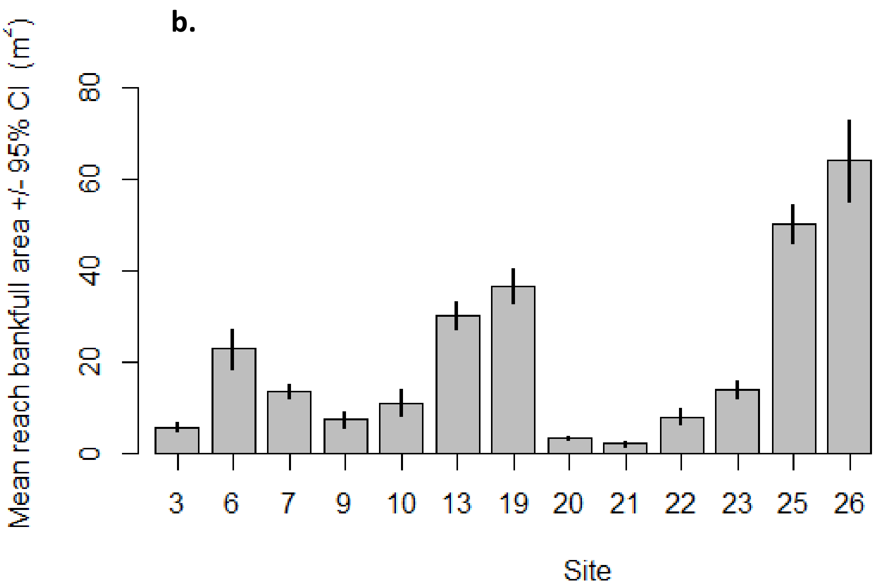
f. Width-to-depth ratio (continued)



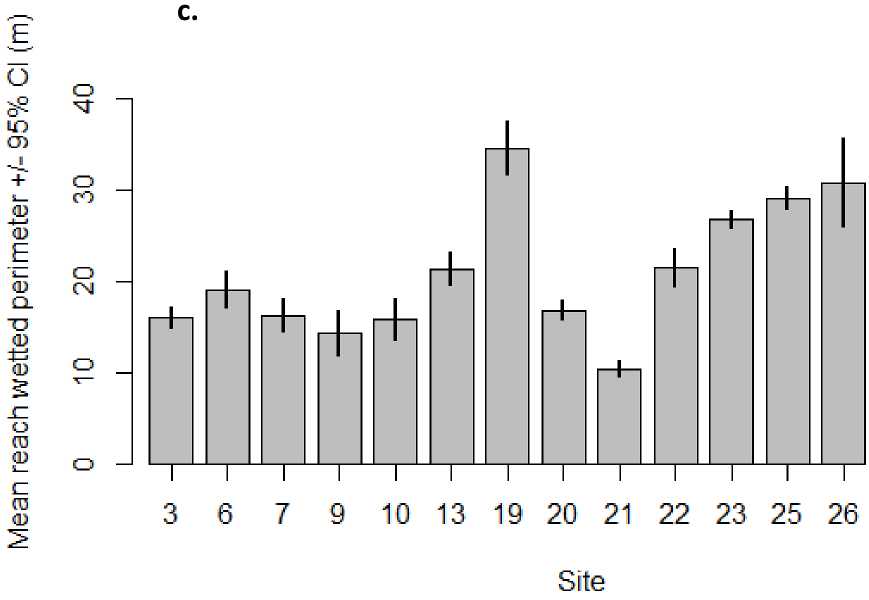
Appendix 6.2: Plots of mean site values

Mean site values of TRAIN group channel reach parameters with ± 95% confidence intervals estimated using bootstrapping techniques (1000 iterations): a) stage; b) cross sectional area; c) wetted perimeter; d) width; e) hydraulic radius; and f) width-to depth ratio.

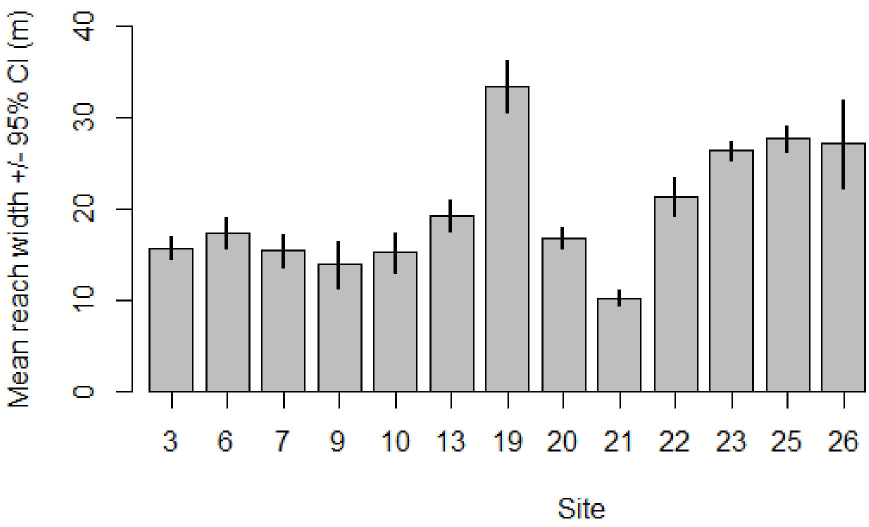




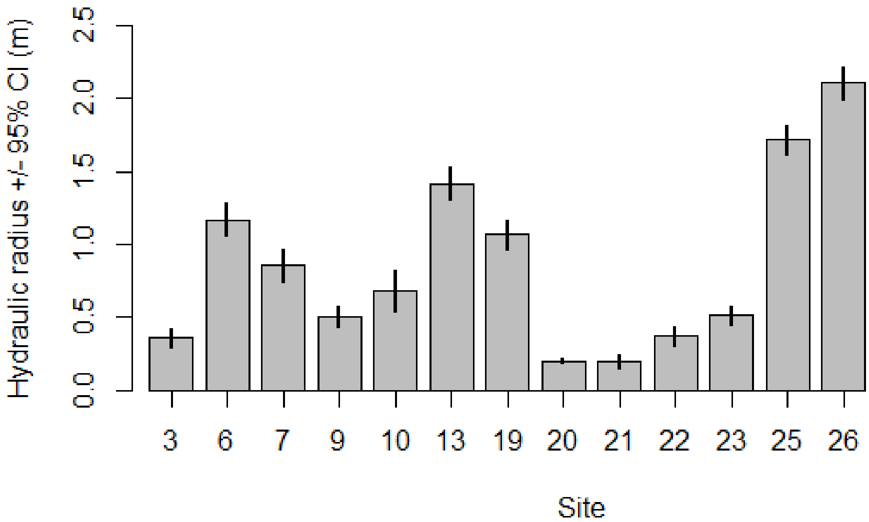
c.


Mean reach wetted perimeter +/- 95% CI (m)
0
10
20
30
40
3
6
7
9
10
13
19
20
21
22
23
25
26
Site

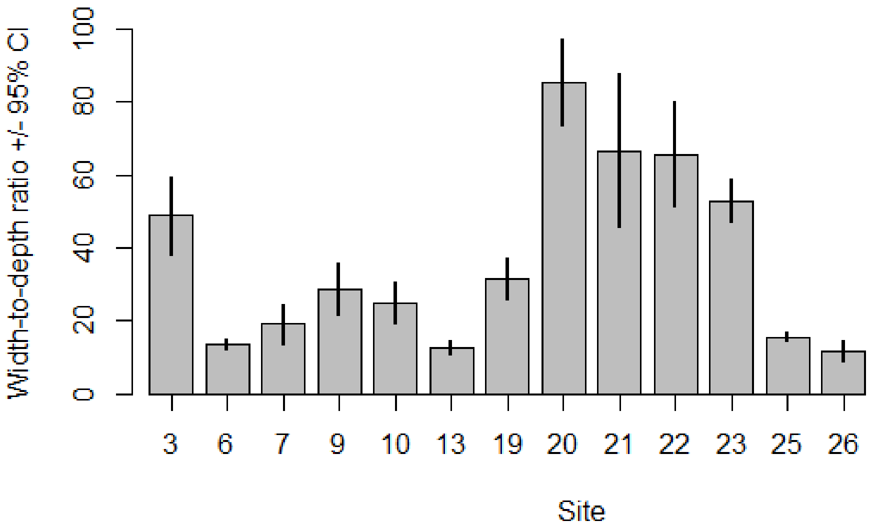
d.


Mean reach width +/- 95% CI (m)
0
10
20
30
40
3
6
7
9
10
13
19
20
21
22
23
25
26
Site

e.


Hydraulic radius +/- 95% CI (m)
0.0
0.5
1.0
1.5
2.0
2.5
3
6
7
9
10
13
19
20
21
22
23
25
26
Site

f.


Width-to-depth ratio +/- 95% CI
0
20
40
60
80
100
3
6
7
9
10
13
19
20
21
22
23
25
26
Site

References

ABDI, H. & WILLIAMS, L. J. 2010. Principal component analysis. *Wiley Interdisciplinary Reviews: Computational Statistics,* 2**,** 433-459.

ALTERMATT, F., SEYMOUR, M. & MARTINEZ, N. 2013. River network properties shape α-diversity and community similarity patterns of aquatic insect communities across major drainage basins. *Journal of Biogeography,* 40**,** 2249-2260.

BAGNOLD, R. 1977. Bed load transport by natural rivers. *Water Resources Research,* 13**,** 303-312.

BARNES, J. B., VAUGHAN, I. P. & ORMEROD, S. J. 2013. Reappraising the effects of habitat structure on river macroinvertebrates. *Freshwater Biology,* 58**,** 2154-2167.

BARTLEY, R. & RUTHERFURD, I. 2005. Measuring the reach-scale geomorphic diversity of streams: Application to a stream disturbed by a sediment slug. *River Research and Applications,* 21**,** 39-59.

BECKER, R. A., CHAMBERS, J. M. & WILKS, A. R. 1988. *The New S Language,* USA, Wadsworth & Brooks/Cole.

BENDA, L., POFF, N. L., MILLER, D., DUNNE, T., REEVES, G., PESS, G. & POLLOCK, M. 2004. The network dynamics hypothesis: How channel networks structure riverine habitats. *BioScience,* 54**,** 413-427.

BIZZI, S. & LERNER, D. N. 2012. Characterizing physical habitats in rivers using map-derived drivers of fluvial geomorphic processes. *Geomorphology,* 169–170**,** 64-73.

BLEDSOE, B. P. & WATSON, C. C. 2001. Logistic analysis of channel pattern thresholds: Meandering, braiding, and incising. *Geomorphology,* 38**,** 281-300.

BOBBI, C. J., WARFE, D. M. & HARDIE, S. A. 2013. Implementing environmental flows in semi-regulated and unregulated rivers using a flexible framework: case studies from Tasmania, Australia. *River Research and Applications***,** n/a-n/a.

BOON, P. J., HOLMES, N. T. H. & RAVEN, P. J. 2010. Developing standard approaches for recording and assessing river hydromorphology: the role of the European Committee for Standardization (CEN). *Aquatic Conservation: Marine and Freshwater Ecosystems,* 20**,** S55-S61.

BRENDEN, T. O., WANG, L., SEELBACH, P. W., CLARK JR, R. D., WILEY, M. J. & SPARKS-JACKSON, B. L. 2008. A spatially constrained clustering program for river valley segment delineation from GIS digital river networks. *Environmental Modelling & Software,* 23**,** 638-649.

BRIERLEY, G., COHEN, T, FRYIRS, K. & BROOKS, A. 1999. Post-European changes to the fluvial geomorphology of Bega catchment, Australia: Implications for river ecology. *Freshwater Biology*, 41 (4), 839-848.

BRIERLEY, G. & FRYIRS, K. 2009. Don't fight the site: three geomorphic considerations in catchment-scale river rehabilitation planning. *Environ Manage,* 43**,** 1201-18.

BRIERLEY, G. J. & FRYIRS, K. 2000. River styles, a geomorphic approach to catchment characterization: Implications for river rehabilitation in Bega catchment, New South Wales, Australia. *Environmental Management,* 25**,** 661-679.

BRIERLEY, G. J. & FRYIRS, K. A. 2005. *Geomorphology and River Mangement: applications of the river styles framework,* Malden MA, Blackwell Publishing.

BRISBANE DECLARATION. The Brisbane Declaration: Environmental flows are essential for freshwater ecosystem health and human well-being. 10th International River Symposium, Brisbane, Australia, 2007. 3-6.

CHESSMAN, B. C., FRYIRS, K. A. & BRIERLEY, G. J. 2006. Linking geomorphic character, behaviour and condition to fluvial biodiversity: implications for river management. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 16**,** 267-288.

CORENBLIT, D., TABACCHI, E., STEIGER, J. & GURNELL, A. M. 2007. Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: A review of complementary approaches. *Earth-Science Reviews,* 84**,** 56-86.

DE ROSE, R. C., STEWARDSON, M. J. & HARMAN, C. 2008. Downstream hydraulic geometry of rivers in Victoria, Australia. *Geomorphology,* 99**,** 302-316.

DICICCIO, T. J. & EFRON, B. 1996. Bootstrap Confidence Intervals. *Statistical Science,* 11**,** 189-212.

DINGMAN, S. L. & SHARMA, K. P. 1997. Statistical development and validation of discharge equations for natural channels. *Journal of Hydrology,* 199**,** 13-35.

DOLLAR, L. H., DOLLAR, E. S. J. & MOOLMAN, J. 2006. Development of an automated desktop procedure for defining macro-reaches for river longitudinal profiles. *Water SA,* 32**,** 395-402.

DPIPWE 2005. Conservation of Freshwater Ecosystem Values Project (CFEV) database. Tasmania: Water and Marine Resources Division, Department of Primary Industries, Parks, Water and Environment.

DPIPWE 2010. Tasmanian Environmental Flows (TEFlows) Project Technical Report. *Water Assessment Aquatic Ecology Report Series.* Hobart, Tasmania: Water and Marine Resources Division, Department of Primary Industries, Parks, Water and Environment,.

DPIW 2007. The Tasmanian Environmental Flows Framework.Technical Report. Hobart, Tasmania: Water Assessment Branch, Department of Primary Industries and Water.

DPIW 2008. Conservation of Freshwater Ecosystem Values (CFEV) Project Technical Report. Hobart, Tasmania: Conservation of Freshwater Ecosystem Values Program, Department of Primary Industries and Water.

ENGLE, V. D., KURTZ, J. C., SMITH, L. M., CHANCY, C. & BOURGEOIS, P. 2007. A classification of U.S. estuaries based on physical and hydrologic attributes. *Environ Monit Assess,* 129**,** 397-412.

FINLAYSON, D. P. & MONTGOMERY, D. R. 2003. Modeling large-scale fluvial erosion in geographic information systems. *Geomorphology,* 53**,** 147-164.

FRISSELL, C. A., LISS, W. J., WARREN, C. E. & HURLEY, M. D. 1986. A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. *Environmental Management,* 10**,** 199-214.

GIPPEL, C. 1985. Changes in stream channel morphology at tributary junctions, Lower Hunter Valley, New South Wales. *Australian Geographical Studies,* 23**,** 291-307.

GOODERHAM, J. P. R., BARMUTA, L. A. & DAVIES, P. E. 2007. Upstream heterogeneous zones: Small stream systems structured by a lack of competence? *Journal of the North American Benthological Society,* 26**,** 365-374.

GORDON, N. D., MCMAHON, T. A., FINLAYSON, B. L., GIPPEL, C. J. & NATHAN, R. J. 2004. *Stream hydrology : an introduction for ecologists* Chichester, West Sussex, Wiley.

GOWER, J. C. 1971. A general coefficient of similarity and some of its properties. *Biometrics,* 27**,** 857–874.

GRANT, G. E., DUVAL, J. E., KOERPER, G. J. & FOGG, J. L. 1992. XSPRO: A Channel Cross-Section Analyzer. Technical Note 387, BLM/SC/PT-92/001+7200 ed. Denver, CO: USDI Bureau of Land Management and USDA Forest Service.

HADDAD, K. & RAHMAN, A. 2011. Selection of the best fit flood frequency distribution and parameter estimation procedure: A case study for Tasmania in Australia. *Stochastic Environmental Research and Risk Assessment,* 25**,** 415-428.

HARDIE, S. A., BOBBI, C. J. & BARMUTA, L. A. 2012. Macroinvertebrate and water quality responses to low flows in Tasmanian rivers. *Low flows report series.* Canberra: National Water Commission.

HORTON, R. E. 1945. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. *Geological Society of America Bulletin,* 56**,** 275-370.

HUGHES, J. M. R. 1987. Hydrological Characteristics and Classification of Tasmanian Rivers. *Australian Geographical Studies,* 25**,** 61-82.

JAIN, V., FRYIRS, K. & BRIERLEY, G. 2008. Where do floodplains begin? The role of total stream power and longitudinal profile form on floodplain initiation processes. *Bulletin of the Geological Society of America,* 120**,** 127-141.

JAIN, V., PRESTON, N., FRYIRS, K. & BRIERLEY, G. 2006. Comparative assessment of three approaches for deriving stream power plots along long profiles in the upper Hunter River catchment, New South Wales, Australia. *Geomorphology,* 74**,** 297-317.

JERIE, K., I., H. & PETERS, D. 2003. *Tasmania's river geomorphology : stream character and regional analysis* Hobart, Nature Conservation Branch, Dept. of Primary Industries, Water and Environment.

JOLLIFFE, I. T. 1973. Discarding Variables in a Principal Component Analysis. II: Real Data. *Journal of the Royal Statistical Society. Series C (Applied Statistics),* 22**,** 21-31.

JURACEK, K. E. & FITZPATRICK, F. A. 2003. Limitations and implications of stream classification. *Journal of the American Water Resources Association,* 39**,** 659-670.

KAUFMAN, L. & ROUSSEEUW, P. J. 1990. *Finding Groups in Data: An Introduction to Cluster Analysis,* New York, Wiley.

KAUFMAN, L. & ROUSSEEUW, P. J. 2005. *Finding groups in data: an introduction to cluster analysis,* Hoboken, New Jersey, John Wiley & Sons.

KNIGHTON, A. D. 1981. Local variations of cross-sectional form in a small gravel-bed stream. *Journal of Hydrology: New Zealand,* 20**,** 131-146.

KNIGHTON, A. D. 1999a. Downstream variation in stream power. *Geomorphology,* 29**,** 293-306.

KNIGHTON, A. D. 1999b. The gravel-sand transition in a disturbed catchment. *Geomorphology,* 27**,** 325-341.

KNIGHTON, A. D. & NANSON, G. C. 1993. Anastomosis and the continuum of channel pattern. *Earth Surface Processes and Landforms,* 18**,** 613-625.

KONDOLF, G. M. 1995. Geomorphological stream channel classification in aquatic habitat restoration: Uses and limitations. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 5**,** 127-141.

KONDOLF, G. M., MONTGOMERY, D. R., PIEGAY, H. & SCHMITT, L. 2003. Geomorphic classification of rivers and streams. *In:* KONDOLF, G. M. & PIEGAY, H. (eds.) *Tools in Fluvial Geomorphology.* Chichester: John Wiley and Sons.

KOVÁCS, J., KOVÁCS, S., MAGYAR, N., TANOS, P., HATVANI, I. G. & ANDA, A. 2014. Classification into homogeneous groups using combined cluster and discriminant analysis. *Environmental Modelling & Software*.

LEOPOLD, L. B., WOLMAN, G. M. & MILLER, J. P. 1964. *Fluvial Processes in Geomorphology,* San Francisco, W.H. Freeman and Co.

LI, Z., WANG, Z., PAN, B., DU, J., BRIERLEY, G., YU, G.-A. & BLUE, B. 2013. Analysis of controls upon channel planform at the First Great Bend of the Upper Yellow River, Qinghai-Tibet Plateau. *Journal of Geographical Sciences,* 23**,** 833-848.

MAECHLER, M., ROUSSEEUW, P., STRUYF, A., HUBERT, M. & HORNIK, K. 2014. cluster: Cluster Analysis Basics and Extensions. . R package version 1.15.2. ed.

MONTGOMERY, D. R. 1999. Process domains and the river continuum. *JAWRA Journal of the American Water Resources Association,* 35**,** 397-410.

MONTGOMERY, D. R. & BUFFINGTON, J. M. 1997. Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin,* 109**,** 596-611.

NEWSON, M. D. & LARGE, A. R. G. 2006. 'Natural' rivers, 'hydromorphological quality' and river restoration: a challenging new agenda for applied fluvial geomorphology. *Earth Surface Processes and Landforms,* 31**,** 1606-1624.

NEWSON, M. D. & NEWSON, C. L. 2000. Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. *Progress in Physical Geography,* 24**,** 195-217.

ORR, H. G., LARGE, A. R. G., NEWSON, M. D. & WALSH, C. L. 2008. A predictive typology for characterising hydromorphology. *Geomorphology,* 100**,** 32-40.

POFF, N. L., RICHTER, B. D., ARTHINGTON, A. H., BUNN, S. E., NAIMAN, R. J., KENDY, E., ACREMAN, M., APSE, C., BLEDSOE, B. P., FREEMAN, M. C., HENRIKSEN, J., JACOBSON, R. B., KENNEN, J. G., MERRITT, D. M., O'KEEFFE, J. H., OLDEN, J. D., ROGERS, K., THARME, R. E. & WARNER, A. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology,* 55**,** 147-170.

POOLE, G. C. Fluvial landscape ecology: addressing uniqueness within the river discontinuum. 2002. Blackwell Publishing Ltd, 641-660.

RAVEN, P. J., HOLMES, N. T. H., CHARRIER, P., DAWSON, F. H., NAURA, M. & BOON, P. J. 2002. Towards a harmonized approach for hydromorphological assessment of rivers in Europe: a qualitative comparison of three survey methods. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 12**,** 405-424.

REINFELDS, I., COHEN, T., BATTEN, P. & BRIERLEY, G. 2004. Assessment of downstream trends in channel gradient, total and specific stream power: a GIS approach. *Geomorphology,* 60**,** 403-416.

RESOURCE PLANNING AND DEVELOPMENT COMMISSION. 2003. *State of the Environment Tasmania 2003* [Online]. Available: http//www.rpdc.tas.gov.au/soer [Accessed 1/11/13].

RILEY, S. J. 1972. A comparison of morphometric measures of bankfull. *Journal of Hydrology,* 17**,** 23-31.

RINALDI, M., SURIAN, N., COMITI, F. & BUSSETTINI, M. 2013. A method for the assessment and analysis of the hydromorphological condition of Italian streams: The Morphological Quality Index (MQI). *Geomorphology*, 180, 96-108.

ROSGEN, D. L. 1994. A classification of natural rivers. *CATENA,* 22**,** 169-199.

SCHMITT, L., MAIRE, G., NOBELIS, P. & HUMBERT, J. 2007. Quantitative morphodynamic typology of rivers: a methodological study based on the French Upper Rhine basin. *Earth Surface Processes and Landforms,* 32**,** 1726-1746.

SCHUMM, S. A. & KHAN, H. R. 1972. Experimental Study of Channel Patterns. *Geological Society of America bulletin,* 83**,** 1755-1770.

SHARPLES, C. 1996. The geology and landforms of northeast Tasmania.

SILVERMAN, B. W. 1986. *Density estimation for statistics and data analysis*, CRC press.

SIPEK, V., MATOUSKOVA, M. & DVORAK, M. 2009. Comparative analysis of selected hydromorphological assessment methods. *Environmental Monitoring and Assessment***,** 1-11.

SOUTH, N. 2009. TRCI Physical Form Field Manual. Hobart: NRM Soiuth.

STEWARDSON, M. 2005. Hydraulic geometry of stream reaches. *Journal of Hydrology,* 306**,** 97-111.

STOTT, T. 2010. Fluvial geomorphology. *Progress in Physical Geography,* 34**,** 221-245.

SULLIVAN, S. M. P., WATZIN, M. C. & HESSION, W. C. 2006. Influence of stream geomorphic condition on fish communities in Vermont, U.S.A. *Freshwater Biology,* 51**,** 1811-1826.

VANNOTE, R. L., MINSHALL, G. W., CUMMINS, K. W., SEDELL, J. R. & CUSHING, C. E. 1980. River continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences,* 37**,** 130-137.

VAUGHAN, I. P., DIAMOND, M., GURNELL, A. M., HALL, K. A., JENKINS, A., MILNER, N. J., NAYLOR, L. A., SEAR, D. A., WOODWARD, G. & ORMEROD, S. J. 2009. Integrating ecology with hydromorphology: a priority for river science and management. *Aquatic Conservation-Marine and Freshwater Ecosystems,* 19**,** 113-125.

VÖRÖSMARTY, C. J., MCINTYRE, P. B., GESSNER, M. O., DUDGEON, D., PRUSEVICH, A., GREEN, P., GLIDDEN, S., BUNN, S. E., SULLIVAN, C. A., LIERMANN, C. R. & DAVIES, P. M. 2010. Global threats to human water security and river biodiversity. *Nature,* 467**,** 555-61.

WOLD, S., ESBENSEN, K. & GELADI, P. 1987. Principal component analysis. *Chemometrics and intelligent laboratory systems,* 2**,** 37-52.

Chapter 7 Conclusion

7.1. Introduction

Rivers are classified out of a basic desire for description and organisation of the world around us, to improve our understanding of fluvial form and processes, and to make better management decisions (Juracek and Fitzpatrick, 2003). This study investigated the development of an objective and quantitative morphological classification to assist in the management of rivers. The purpose of the study was to increase understanding of the hydromorphology of north-eastern Tasmanian rivers to assist in their management. The aim of the study is to develop an objective and quantitative broad morphological typology of Tasmanian rivers that can in the future be combined with existing hydrological typology to develop a hydro-morphological classification of Tasmanian rivers and streams. To achieve this aim, several sub-studies were conducted in Chapters 2 to 5 to determine suitable methods and estimates of parameters for later use in the development of a hydro-morphological typology. The sub-studies focussed on the estimation of the magnitude and frequency of small floods, investigation of bankfull channel morphometry, analysis of the first order estimates of peak discharge of small floods, and assessment of the hydro-morphological characteristics of different river basins. Chapter 6 uses the results from the sub-studies to conduct an exploration of the variability in catchment and channel metrics in an attempt to develop a method of morphological typology for north-eastern Tasmanian rivers. A summary of the results is provided in Section 7.2.

7.2. Summary of results

As well as providing estimates of parameters for use in a morphological typology of north-eastern Tasmanian rivers, chapters 2 – 5 of this thesis each present separate and complete studies with their own results and discussions. The first sub-study estimated the magnitude frequency of small floods ($T \leq 10$ years) for north-eastern Tasmanian streamflow stations using both partial and annual series data (Chapter 2). Empirical comparisons were made between flood frequency estimates based on the annual series data set, those based on the partial series, and the Langbein method of converting annual series average recurrence intervals to partial series intervals. Large differences were found between annual and partial series flood frequency estimates made using Northern Tasmanian stream-flow data for average recurrence intervals of less than five years, similar to the findings of other studies. Annual series estimates were one third the magnitude of partial series estimates at T = 1.1 years, but the two series converged as average recurrence interval increased until there was no significant difference between the two series at T = 5 years. At low recurrence intervals there were relatively small differences between the various partial series estimates for a site made using different discharge thresholds, especially in comparison to the differences between partial series and annual series flood frequency estimates. This suggests that the definition of the partial series data set may not be of critical importance at low average recurrence intervals, although more research is required to confirm this.

Chapter 2 also found that Langbein's equation did not provide a suitable empirical method to convert annual series flood frequency estimates to partial series estimates at average recurrence intervals of less than five years. Langbein adjusted annual series estimates were three quarters the magnitude of partial series estimates at T = 1.1 years. These results suggest that both the annual series and the Langbein adjusted annual series significantly underestimate the magnitude of frequent floods and should not be used at average recurrence intervals of less than five years. They indicate that the partial series should be used for estimates of high frequency-low magnitude floods (T < 5 years).

To assist in the determination of bankfull stage from plotted channel cross-sections, the second sub-study (Chapter 3) evaluated two quantitative methods for determining bankfull stage: the minimum width-to-depth ratio and the first maximum of the bench index. Each method was examined and compared to qualitative estimates of bankfull stage on 89 cross-sectional channel surveys of North-eastern Tasmanian Rivers. Results indicated that while neither method offered a suitable stand-alone means for estimating bankfull stage, in combination they may provide a means to approximate the range of bankfull stage. The results also highlight the large variability in channel morphology along a reach.

First order estimates of the peak discharge of small floods at ungauged sites in north-eastern Tasmania were developed in Chapter 4. Using power-law equations relating the peak discharge of floods with average recurrence intervals ranging from 1.1 to 10 years to catchment area (A_d) and data from 13 stream gauging stations, the methods developed in Chapter 2 were used to estimate the peak discharge of small floods and develop discharge-catchment area relationships. The impact of the choice of annual or partial series flood frequency estimates on the scaling of the power-law relationship was also examined. Results suggested that the discharge associated with a flood with two year average recurrence interval may be estimated by 0.45 $A_d^{0.9}$. Intra-regional variation in the relationship between discharge and catchment area identified a group of northward draining rivers in north-eastern Tasmania that plotted as negative residuals and a group of internally draining sites which plotted as positive residuals.

Building on the results from earlier chapters, Chapter 5 evaluated three hydro-morphological characteristics of north-eastern Tasmanian Rivers: drainage density, bankfull frequency and stream-power. The range and variation in drainage density values was examined and found to broadly reflect variation in precipitation, elevation and geology. The two groups of rivers identified in Chapter 5 were found to have different drainage density ranges. Catchments draining northwards or eastwards to the coast were found to have drainage densities > 2 km km^{-1}, while internally draining catchments were found to have drainage density < 2 km km^{-1}.

In the second part of Chapter 5 the estimation of bankfull discharge was investigated. Attempts to accurately measure bankfull discharge at the study sites using field techniques were unsuccessful, as was the use of commonly used flow resistance equations. Large variances were found between estimates from different flow resistance equations, particularly at sites with deeper channels and high hydraulic radius. Previous studies have estimated that the average recurrence interval of bankfull discharge in north-eastern Tasmanian rivers falls between 1.11 and 3.5 years. Although bankfull discharge magnitude frequency is unlikely to be constant along a river or throughout a region, many other studies have adopted a two year average recurrence interval as a proxy for bankfull discharge, and was a suitable approximation for the average recurrence interval of bankfull discharge in north-eastern Tasmanian rivers.

The first order estimates of peak discharge of small floods developed in Chapter 5 were used to develop suitable methods to estimate stream-power values across north-eastern Tasmania in the third part of Chapter 5. Substantial variability in the downstream trends in stream-power was found in the Pipers, Ringarooma and Scamander rivers. These rivers were found to have different longitudinal trends and to deviate from the general downstream stream power trends found elsewhere. There was some evidence of an association between channel morphology and stream power, with high *WD* values/ low *R* values occurring at locations with high stream power.

In Chapter 6, the river and catchment metrics developed in earlier chapters were used in conjunction with multivariate statistical analysis of channel cross-sectional data from field surveys to investigate variability in channel morphology and develop a quantitative morphological typology. A strong source of underlying variability in the dataset was found to occur along an orthogonal axis which had high values of width-to-depth ratio at one end and high hydraulic radius values at the other. While the PCA analysis was able to identify two groupings with membership based on either high width-to-depth ratio or high hydraulic radius, methods to derive the groupings of sites based on channel parameters using remote parameters were generally unsuccessful; combinations of the remote parameter values determined using PCA were unable to reproduce natural grouping identified using channel parameters. It was suggested that within reach variability confounded any attempts to identify between reach variability. However drainage density was identified as a strong remotely sensed predictor variable. The methods used in this study offer insights into the development of an objective and quantitative morphological typology of north-eastern Tasmanian rivers. The results suggest that localised and reach scale factors have more influence on channel morphology than catchment controls in north-eastern Tasmanian rivers. This has implications for the use of remotely sensed data and GIS tools in the study of regional hydromorphological characteristics.

This final chapter summarises the results from previous chapters, combining the different findings and considering the results as a whole. The overall results are placed within the context of the Tasmanian landscape and their transferability is considered. Finally, this chapter looks at emerging technologies, limitations of the study are discussed and directions for future study identified.

7.3. Implications of the results

7.3.1. The diversity of north-east Tasmanian rivers and streams

This study considered the rivers of north-eastern Tasmania, and the results from this study must be framed in relation to the distinctive Tasmanian landscape and hydrology. Australia has rivers different to those found in other parts of the world (Brierley and Fryirs, 2005), and it may be equally valid to suggest that Tasmanian rivers and streams display significant differences from those in both mainland Australia and the rest of the world.

The study found considerable variability in channel morphology both along a reach and between sites. The high within reach variability contributed to the failure to identify distinct and meaningful groupings of sites based on standardised channel morphology parameters. The failure to find any meaningful grouping of sites using remotely sensed parameters suggests that localised and reach scale factors have more influence on channel morphology than catchment scale controls in north-eastern Tasmanian rivers.

The study also considered regional variability in north-eastern Tasmania. The distribution of sites around the regression line in the analysis of the relationship between catchment area and discharge for small floods conducted in Chapter 4 identified a group of internally or east coast draining rivers plotting as positive residuals and a group of internally draining rivers as negative residuals. The grouping of these sites broadly correlated with the drainage density patterns identified in Chapter 5, with catchments draining northwards or eastwards to the coast having drainage densities > 2 km km-1, while internally draining catchments had drainage density < 2 km km-1.

The two groups of sites identified in this study reflect the hydrological grouping of rivers into high variability HV and low variability (LV) undertaken by DPIPWE (2010). North-eastern Tasmanian rivers which discharge to the north coast have been characterized as LV rivers, having generally higher and more consistent baseflows, no cease-to-flow periods, and a lower magnitude of difference between high flow events and mean flows. In contrast, HV sites have a larger range of flow conditions, with more variable baseflows, and large floods, often of very high magnitudes compared to their average baseflows (DPIPWE, 2010).

The positive residual group identified in catchment area-discharge relationship from this study had a greater magnitude frequency of small floods then other sites in the region, and these sites correspond to the HV group whose frequency of bankfull flow is consistently higher than at LV sites (DPIPWE, 2010). Unfortunately, a full hydrological categorisation of north-eastern Tasmanian catchments using the HV/LV methodology has not been undertaken by DPIPWE, so the validity of this relationship between channel morphology and HV/LV rivers cannot be further investigated at this time.

The grouping of sites identified in this study are also similar to that found by Knighton (1987) in a regional flood analysis and also reflect the patterns found by Hughes (1987), in a hydrological classification of Tasmanian rivers. However in making links between the findings of different studies of north-eastern Tasmanian rivers it should be noted that they are not independent of each other. All flood frequency related studies from the north-east region necessarily use data from the same limited group of stream flow gauging sites. Also the DPIPWE grouping is based on a very small sample.

The significant differences found between HV and LV rivers in terms of geomorphology of the river channel and the heterogeneity of instream habitats (DPIPWE, 2010) was not reflected in the findings of this study. This study found no correlation between channel morphology and the groupings identified. While a strong underlying variability in channel morphology was identified along a high width-to-depth ratio- high hydraulic radius axis, the spread of sites along that axis did not reflect the groupings based on hydrological variability. Rather than relating to hydromorphological variability, it is likely that the high bank angle that was associated with LV rivers was a result of antecedent morphology, as the group of north-eastern streams which flow north to Bass Strait (LV rivers) have valleys through an uplifted old coastal plain, creating terraces on the lower reaches of these rivers (Jerie et al., 2003). DPIPWE (2010) found HV sites had a wider range of instream heterogeneity of channel form, and there was a slight trend in this study for inwardly draining sites to have higher channel variability (Chapter 3).

7.3.2. Implications of the study results

The importance and influence of river physical habitat on freshwater ecology is widely recognised (Maddock, 1999; Orr, 2008), and as a consequence the use of geomorphic or hydromorphic templates has been widely adopted in a range of aquatic ecology and environmental flow applications. However the study results raise questions about the role of hydromorphic templates and the classification of rivers more generally.

The results of this study indicate that rivers from north-east Tasmania may have significant differences to those found elsewhere. Downstream variation in stream power in the study rivers, for example, was found to be highly variable and have patterns unlike generalised models or those from studies in mainland Australia. The variability between rivers and departure from theorized models of downstream stream-power variability is likely to be a result of local topographic differences. Each of the three study rivers arise in mountain ranges and fall relatively steeply before travelling a short distances of the coast. However each has significant differences in surface geology and hydrology.

The scaling factor in the relationship between catchment area and discharge was also found to be much more linear than in other parts of Australia. As well as being a result of differences in hydrology and landscape setting, this may reflect differences in land-use and settlement patterns. Australian river regulation and water usage is generally higher in the lower parts of catchments, and human settlements are clustered along the coast. Consequently these lower parts of the catchments may contribute less discharge than upper catchment areas which are often much less impacted. North-eastern Tasmanian rivers are largely unregulated, and human habitation and water usage is higher in inland areas away from the coast. These differences may result in proportionally more discharge being added in downstream catchment areas in North-eastern Tasmania than elsewhere in Australia. More generally, the channel morphology of north-eastern Tasmanian rivers does not seem to follow some of the general downstream trends found elsewhere (Figure 1.2). Also, the influence of channel planform on channel morphology types that exists in other locations may not present in the same way in north-eastern Tasmanian rivers.

In addition, catchment scale remotely sensed parameters were shown to be unable to identify groupings of sites based on channel morphology. These results suggest that the reach scale variability in morphology, which is a result of localised features and processes, renders catchment scale controls on channel morphology meaningless. Regional scale differences in climate, geology, and topography are generally understood to exert controls upon the general geomorphic processes developed upon a landscape (Montgomery, 1999), with processes operating at a large scale delimiting the types of fluvial features and processes that can occur at smaller scales (Frissell et al., 1986). The deviation from these general models observed in north-eastern Tasmanian rivers raises questions about the suitability of using hydromorphic templates based on hierarchical nested controls and developed in locations with very different stream characteristics. The high variability in channel morphology found in this study also suggests that defining homogeneity within the heterogeneity of north-eastern Tasmanian river systems may be difficult, making decisions on class numbers and boundaries more dependent on the subjective judgment of the practitioner of river classification. The high variability in north-eastern Tasmanian river channel morphology, both along a reach and between sites and their departure from generalised fluvial models has significant implications for the understanding and management of rivers.

Understanding the implications of the results requires understanding as to how transferable they are to other north-east Tasmanian rivers, as well as to the broader population of Tasmanian, Australian and rest of world rivers. Are the results of this study relevant? This study has used only a small sample of an effectively infinite population of north eastern Tasmanian river channel morphology. The use of such a small sample means that statistically the sample sites may not be reflective of the wider diverse population of Tasmanian rivers. Despite subjective attempts throughout the study to take a 'representative' sample, the results are not necessarily transferable. However the presence of variability does not mean that the results are not relevant. Recognizing that every location is potentially unique does not mean that generalisations are meaningless. Regularities in time and space can still be observed as repeated patterns of landforms, and interpretations of these patterns can support efforts to meaningfully transfer understandings (Brierley et al., 2013).

Brierley et al., (2013) argue for a 'reading the landscape' approach where understanding of the landscape is assembled through multiple propositions and explanations, embracing inherent uncertainties. Rather than being a universalizing epistemology or a mechanism to develop a 'single knowable truth', the approach is framed as a starting point for a pluralist activity that is not restricted to particular disciplinary or methodological framings. There is no single, 'right' way to read a landscape. Different readings can be made based on the questions asked, the methodology used to generate data (whether qualitative or quantitative), and the way data are analysed and interpreted (Brierley et al., 2013).

The results of the study raise questions about the relevance of generalised river classification schemes to north-eastern Tasmania, and how management actions are framed in relation to the north –eastern landscape. Approaches such as River Styles, which has been widely adopted in Tasmania, advocate an open ended approach which does not limit the river classification types to a rigid pattern of generalisations. This flexibility allows River Styles to be adapted to reflect local conditions, but also places more requirements for subjective judgement on the practitoner. Despite the veneer of objectivity granted by the application of various statistical procedures, approaches to river classification ultimately rely upon expert judgement and intuition to classify phenomena (Tadaki et al., 2014). Tadaki et al. (2014) point out that classification schemes are not objective or value-neutral, but instead are institutional projects that propose and embed particular priorities; river classifications not only describe the world; they propose value-laden decision-making rationalities.

Since approaches to geomorphic inquiry and their application to environmental management reflect particular epistemic cultures, questions must be raised as to whose frameworks should be used to interpret landscapes, and what qualifications and skills should be deemed appropriate, and why (Brierley et al., 2013). Such considerations also apply to this study. The suggestion for a simplified hydromorphological typology in this paper requires consideration of how river classifications perform and embed particular environmental rationalities, which give rise to particular framing effects in a given location. Scientists must become ethically concerned with how their classifications reproduce particular decision-making mindsets, and should engage more directly with their implications (Tadaki et al., 2014).

The use of geographic information system (GIS) tools is essential for scientists and river basin managers to characterize riverscapes and explore biogeomorphologic processes over large channel networks (Roux et al., 2014). The development of new analysis techniques and the increasing quality and quantity of remotely sensed data (e.g. LiDAR) offer the potential for the 'sampling' of rivers to be undertaken at very fine resolutions. These new developments have seen the 'remote sensing of rivers' emerging as a sub-discipline of fluvial geomorphology (Bizzi and Lerner, 2013).

A central theme of these new methods is a move away from qualitative and spatially limited quantitative models which rely on a limited number of measurements spread widely throughout a river basin towards quantitative and spatially comprehensive ecology and landscape ecology methods that require information on the spatial distribution of organism-scale habitats throughout entire river systems (Carbonneau and Piegay, 2012). Leading the development of these new tools was Alber and Piégay (2011), who developed a methodological framework for delineating and characterizing fluvial features based on raw data available at a regional scale. The combination of information extracted from different sources (e.g. vector hydrographic network, DEM, archives aerial photos) allows the user to extract geomorphic characteristics of fluvial features at different spatial levels. Another prominent example of these new tools is “FluvialCorridor”, designed to explore riverscape features at reach to network scales from existing vector and raster layers (Roux et al., 2014). These new approaches have also developed methods for extracting primary parameters such as width, depth and particle size, which are then used to derive second-order geomorphic and hydraulic variables such as velocity and stream power (Carbonneau and Piegay, 2012).

However at the same time that sampling error decreases as a result of the hugely increased sample size offered by the remote sensing and new methods, uncertainty and measurement error increases. Large data sets offer immense opportunities for the development of local place-based knowledge, but they also present a temptation to adopt standardized approaches at the expense of locally tailored interpretations (Brierley et al., 2013). The derivation of secondary parameters from measured first order parameters for example, uses broad generalizations that overlook local variability. The consideration of bankfull stage estimation techniques in Chapter 3 of this study highlights how poorly some parameter derivation models can perform. In these new systems the preference is towards smoothing of data over consideration of detail. Problems can also occur with some of the new tools when used at a regional scale. Input parameters often do not handle the inherent size effect of fluvial longitudinal patterns (Roux et al., 2014).

These new methods also raise questions about their integration with other models. In the development of environmental flow levels, for example, the Environmental Limits of Alteration (ELOHA) (Poff et al, 2010) suggests that flow alteration–ecological response relationships are developed for each river type by building up a body of evidence. Resolving the requirements for breaking a river into classes, as required by applications such as ELOHA, with the continuous, spatially comprehensive new models has yet to be resolved.

7.3.2. Limitation of the study and future directions for research

Limitations of the individual study results have been outlined in each chapter, and many of these limitations also apply to the study as a whole. Sampling variability adds uncertainty to all environmental studies, and is a major limitation of this study. This is discussed in Section 7.3.1 (above). Patterns of channel morphology may have been confounded by the inclusion of rivers with a range of geomorphic conditions; as more variability is introduced by the inclusion of cross-sections from rivers at different stages of geomorphic recovery following disturbance (Derose et al., 2008).

Future directions for fluvial geomorphology research in north-eastern Tasmanian rivers include further defining the characteristics of the groupings of rivers identified in this study and determining their broader applicability. The acquisition of new remotely sensed data sets and the adoption of new GIS tools offer new research opportunities into the diverse and increasingly threatened rivers of Tasmania.

More broadly, important directions in the continuing development of the hydromorphology of rivers and river remote sensing will include reconciling form and process representations across different spatial and temporal scales. It is also necessary to resolve the dichotomy between the variability in river form and process, and the necessity of reducing the complexity sufficiently that an understanding of the links between the effects of landscape/hydrological alterations and ecological responses can be made.

7.4. Conclusion

Although the study has not achieved its aim of developing an objective and quantitative broad morphological typology of Tasmanian rivers, it has achieved its purpose of increasing understanding of the hydromorphology of north-eastern Tasmanian rivers, and it is hoped that this knowledge will assist in their management.

References

ALBER, A. & PIEGAY, H. 2011. Spatial disaggregation and aggregation procedures for characterizing fluvial features at the network-scale: Application to the Rhône basin (France). *Geomorphology,* 125, 343–360.

BIZZI, S. & LERNER, D. (2013). The use of stream power as an indicator of channel sensitivity to erosion and deposition processes. *River Research and Applications*, 31, 16-27.

BRIERLEY, G. J. & FRYIRS, K. A. 2005. *Geomorphology and River Mangement: applications of the river styles framework,* Malden MA, Blackwell Publishing.

BIZZI, S. & LERNER, D. (2013). The use of stream power as an indicator of channel sensitivity to erosion and deposition processes. *River Research and Applications*, 31, 16-27.

BRIERLEY, G., FRYIRS, K., CULLUM, C., TADAKI, M., HUANG, H. and BLUE, B. 2013. Reading the landscape: Integrating the theory and practice of geomorphology to develop place-based understandings of river systems. *Progress in Physical Geography*, 37(5), 601-621.

CARBONNEAU, P. & PIEGAY, H. 2012. Introduction: The growing use of imagery in fundamental and applied river sciences. *Fluvial Remote Sensing for Science and Management*, 1-18.

DE ROSE, R. C., STEWARDSON, M. J. & HARMAN, C. 2008. Downstream hydraulic geometry of rivers in Victoria, Australia. *Geomorphology,* 99, 302-316.

DPIPWE 2010. *Tasmanian Environmental Flows (TEFlows) Project Technical Report*. Water Assessment Aquatic Ecology Report Series. Hobart, Tasmania: Water and Marine Resources Division, Department of Primary Industries, Parks, Water and Environment.

FRISSELL, C. A., LISS, W. J., WARREN, C. E. & HURLEY, M. D. 1986. A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. *Environmental Management,* 10, 199-214.

HUGHES, J. M. R. 1987. Hydrological Characteristics and Classification of Tasmanian Rivers. *Australian Geographical Studies,* 25, 61-82.

JERIE, K., HOUSEHOLD, I. & PETERS, D. 2003. *Tasmania's river geomorphology : stream character and regional analysis* Hobart, Nature Conservation Branch, Dept. of Primary Industries, Water and Environment.

JURACEK, K. E. & FITZPATRICK, F. A. 2003. Limitations and implications of stream classification. *Journal of the American Water Resources Association,* 39, 659-670.

KNIGHTON, A. D. 1987. Streamflow characteristics of northeastern Tasmania: I. regional flood flows. *Papers & Proceedings - Royal Society of Tasmania,* 121, 23-33.

MADDOCK, I. 1999. The importance of physical habitat assessment for evaluating river health. Freshwater Biology, 41, 373-391.

MONTGOMERY, D. R. 1999. Process domains and the river continuum. *JAWRA Journal of the American Water Resources Association,* 35, 397-410.

ORR, H. G., LARGE, A. R. G., NEWSON, M. D. & WALSH, C. L. 2008. A predictive typology for characterising hydromorphology. *Geomorphology,* 100, 32-40.

POFF, N. L., RICHTER, B. D., ARTHINGTON, A. H., BUNN, S. E., NAIMAN, R. J., KENDY, E., ACREMAN, M., APSE, C., BLEDSOE, B. P., FREEMAN, M. C., HENRIKSEN, J., JACOBSON, R. B., KENNEN, J. G., MERRITT, D. M., O'KEEFFE, J. H., OLDEN, J. D., ROGERS, K., THARME, R. E. & WARNER, A. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology,* 55, 147-170.

ROUX, C., ALBER, A., BERTRAND, M., VAUDOR, L. and PIEGAY, H. 2014. "FluvialCorridor": A new ArcGIS toolbox package for multiscale riverscape exploration, *Geomorphology*.

TADAKI, M., BRIERLEY, G. & CULLUM, C. (2014). River classification: theory, practice, politics, *WIREs*, 2014, 1, 349-367.